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HYDROGEN AND PREHEAT MANAGEMENT IN WELDED HIGH STRENGTH STEEL FOR DEFENSE APPLICATIONS

TTCP Project MAT-TP1-0-13

FINAL REPORT

D.L. Olson

July 15, 1999

U.S. Army Research Office

Colorado School of Mines
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<u>**Table of Contents**</u>

1.0 EXECUTIVE SUMMARY

With the need for new approaches to improve hydrogen management in higher strength steels, three tasks, each with its special focus and potential contributions, were established to promote cooperative research with TTCP operating assignment 013. These efforts are timely due to the introduction of even higher strength steels in Naval structures and defense hardware. These steels use new concepts of strengthening (i.e. precipitation) and not just the traditional eutectoidal decomposition. As the strength level increases the amount of allowable diffusible hydrogen content decreases and has decreased to a level of the uncertainty in the practice of diffusible hydrogen measurement. At these lower hydrogen levels, the hydrogen distribution is as important as the average weld metal diffusible hydrogen content.

The three tasks are the following:

Task 1:	Develop new weld hydrogen cracking tests.
Task 2:	Determine relationships between welding parameters (including hydrogen content) on multiple pass weld transverse cracking.
Task 3:	Develop high strength steel filler metal to be used without preheat.

Contributions made for each task are discussed.

Task 1: With the use of the new higher strength steels for defense applications, the requirements for supporting quality assurance practices are essential. The TTCP members contributed to the development and evaluation of various testing methodologies. The task with its multiple contributions, allowed for a comprehensive evaluation as how hydrogen cracking tests relate to structural integrity. The tests included the longitudinal restraint cracking test, modified gapped bead on plate test, modified WIC test, modified cruciform test, fatigue life in hydrogen environment (a concern related to the used of cathodic protection), and materials testing using K_{IEAC} and J-Integral fracture testing. The results of these activities have been presented and published, and some of these tests have advanced as an improvement to the existing specifications. The issues of repair welding, such as establishing a worst case scenario for assessing hydrogen cracking susceptibility has been initiated and is in progress.

Task 2: In the search for more productive and high integrity welding of higher strength steel, the requirements to understand the relationship between welding practices and process parameters on hydrogen cracking susceptibility are necessary. The process parameters include hydrogen cracking relationship to heat input and hydrogen content, hydrogen arc sensing to predict hydrogen content and distribution, hydrogen content in multi-pass welds, and the role of the carbon content on hydrogen cracking. Welding practice activities include crack mapping in a T-Butt joint under HIC conditions, characterizing undermatched weldments, and inspecting structures for hydrogen cracking with various delay times; especially needed for repair welding. The concept of electrotransport to reduce diffusible hydrogen levels during the weld thermal cycle has been reviewed. The selection of welding process practices and parameters for welding higher strength steels has become more engineering based with the cooperative activities of the TTCP members.

Task 3: The role of welding consumables in controlling the tendency to hydrogen crack during

welding of higher strength steels was investigated by various TTCP members and new consumables have been developed and evaluated for use in Naval construction. New methods to eliminate hydrogen cracking by way of the welding consumable has been developed and transferred to the defense industry for implementation. The activities included a comprehensive effort to alloy the welding consumables to achieve acceptable mechanical properties and maintain very low diffusible hydrogen content. This effort resulted in the use of weld metal hydrogen traps, use of fluoride addition to reduce the hydrogen pick up, and use of the proper matching of weld metal to the base metal composition reduce the tendency for hydrogen localization. All three approaches were successful and are being implemented at the various welding consumable manufacturers of MMA and FCA welding consumables. ULCB gas metal arc wires were developed and evaluated for mechanical properties and weldability requirements. The ULCB wires are being further evaluated in Naval construction.

1.1 Highlights of Accomplishment

- **Hydrogen Cracking Tests**

Hydrogen cracking tests are being evaluated for their ability to relate cracking tendency to welding practice, weld configuration and associated materials. Efforts have been particularly focussed on transverse weld metal cracking. Some of this work has resulted in the modification of an ASTM Testing Specification. The development of a new modified curciform (WIC) test, which is very successful in detecting the propensity of transverse cracking in multipass welds, has been achieved. Also a new life analysis procedure using a "fatigue intensity factor" has been developed which clearly differentiates between mechanical and hydrogen cracking affected life of steel components. The length of time necessary after repair welding before inspection for hydrogen cracking should be performed has been determined. This repair welding information is essential to extend the life of high strength steel assemblies. A new initiative will address criteria for the testing of weld repair procedures: the worst case scenario.

- **Austenite Decomposition Temperature**

A new concept using the austenite decomposition temperature as an indice for predicting diffusible hydrogen content and distribution is being developed. Comparison of the austenite decomposition between the weld deposit and the base material has been shown to predict whether the hydrogen distribution will promote cracking in the weld metal or in the heat affected zone. This indice will be of value in the selection of the proper welding consumable for a given high strength steel.

- **Hydrogen Arc Sensor**

A hydrogen arc sensor has been developed which is able to determine the hydrogen content in the arc. These hydrogen arc signals have been directly related to the weld metal hydrogen content. This in process hydrogen analysis will greatly improve quality assurance and gives an indication of improper hydrogen conditions while the welding.

- **Arc Plasma Chemistry for Low Hydrogen Uptake**

The introduction of small amounts of fluorine into the welding plasma under controlled oxygen contents has been shown through both theoretical and experimental investigations to reduce the diffusible hydrogen content in high strength steel weld deposits. The fluorine is introduced as

controlled amounts of specific fluorides in the welding consumable. Implementation of this approach of hydrogen management will require further research and the close cooperation with the welding consumable manufacturers.

- **Hydrogen Trapping**

The concept of using specific hydrogen traps in weld metal has been shown theoretically to be a promising method of reducing and controlling diffusible hydrogen in high strength weldments. The shared knowledge of the diffusible and residual hydrogen contents, obtained by the various TTCP members has given preliminary indications that this concept will work if properly applied. Experimental work involving specially prepared welding consumables is in progress and will evaluate our ability to put this concept into practice. Success of the use of hydrogen traps in steel components for hydrogen management has been demonstrated by USA-Army Benet Lab.

- **Preheat Free MMA, GMA and FCA Welding Consumable**

An ultra low carbon bainitic (ULCB) welding wire composition which has shown very acceptable mechanical properties and welding performance has been developed and is being scaled up to production size heats for final evaluation.

- **Advanced Analytical Practices for Weld Hydrogen Content**

Analytical methods have been developed to evaluate the hydrogen content across the weld as well as the diffusible hydrogen content. The hydrogen distribution is becoming a more serious issue with the use of steels of ever-increasing strength levels. Laser Induced Breakdown Spectroscopy has been used to demonstrate that the weld hydrogen content is not uniform in its distribution but has localized high contents which should be of major concern to the integrity of high strength steel welds. These localized hydrogen contents are most likely the cause in the spread of the measured hydrogen cracking results in welds that have acceptably low measured diffusible hydrogen contents.

2.0 INTRODUCTION

Despite 50 years of research into the prevention of hydrogen induced cracking in weldments, the form of cracking is still the most serious problem facing the steel fabrication industry today. Increased performance for defense platforms requires stronger lighter structures which have largely been obtained using high strength steels. As th strength is increased, so is the risk of hydrogen induced cracking after welding. To address this issue, the management of hydrogen, and the elimination of hydrogen induced cracking during the welding of high strength structural steels, has been made the focus of an TTCP. The operating assignment is as follows:

Assignment Title: **Reference No:** MAT-TP1-0-13

HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENSE APPLICATIONS

Focus Officer: Prof. D.L. Olson **Status:** Ongoing **Type:** Operating

Start Date: 1994 **Estimated Completion Date:** 1999

	Aus	Can	NZ	UK	US
Estimated Manpower Effort:	min 1.5	min 2	----	min 1	min 10

Principal CTA: Cost Effective Metallic Materials

Associated CTA: Life Estimation and Failure Mechanisms

Defence Relevance: The applications of high strength steels in structural assemblies allows for higher combat performance. Two factors which have limited its application are (1) a very restrictive weld processing parameter window and (2) the management of hydrogen.

Scientific Objective: To investigate metallurgical and physical concepts which can be used to increase high strength steel weldment reliability. This is to include: (1) strengthening and fracture retarding mechanistic approaches for improved weld steel properties and (2) hydrogen management techniques for reducing the susceptibility of high strength steel weldments to hydrogen damage.

Outline Program (Start to Finish): The assignment has been divided into three special tasks: (1) development of new hydrogen cracking tests that evaluate the susceptibility of weld metal to hydrogen transverse cracking; (2) determination of the relationship between weld metal hydrogen content and susceptibility to transverse weld metal hydrogen of multipass weldments, and (3) development of a family of high strength steel filler metals that can deposit crack-free weld metal without the need for preheat or post weld soaks. Each of these tasks has an assigned leader who will coordinate the activities of the respective contributing countries. During the third year, a weld metal damage conference will be held to review the state of the art, significant finding, and mid project corrections. A round robin testing exercise will be carried out in the fifth year.

3.0 PARTICIPANTS

Australia : Brian Dixon, Len Davidson, Bob Phillips, Ian French, Stan Lynch,

Canada : Calvin V. Hyatt, J.E. MacBraid, Jim Gianetto, Brian Graville

United Kingdom : Jon Butler, Richard Pargeter

United States : Richard J. Wong, John Deloach, Joe Blackburn, Gene Frankie, Greg N. Vigilante, John H. Underwood, Paul Cote, David L. Olson, Tom Wildeman, Glen R. Edwards, Stephen Liu, T. DebRoy, Mark Eberhart, Stan Ferree, Vincent van der Mee, Roger Stanton, Gerald L. Spencer, Bob Weber, Chad A. Lensing, Yeongdo Park, Iman S. Maroef, David Smith.

4.0 Hydrogen Management

Operating Assignment Tasks

(July, 1999)

TTCP PTP1-013

Special Topics in Welding:
Hydrogen Management in High Strength Steel Weldments

TASK 1: RESEARCH AND DEVELOPMENT OF NEW WELD HYDROGEN CRACKING TESTS

TASK 2: DETERMINATION OF THE RELATIONSHIP BETWEEN WELDING PARAMETERS (INCLUDING HYDROGEN CONTENT) ON MULTIPLE PASS WELD TRANSVERSE CRACKING

TASK 3: DEVELOPMENT OF HIGH STRENGTH STEEL FILLER METALS TO BE USED WITHOUT PREHEAT

4.1 TASK 1

Research and Development of New Weld Hydrogen Cracking Tests

TASK 1

RESEARCH AND DEVELOPMENT OF NEW WELD HYDROGEN CRACKING TESTS

1. Longitudinal Restraint Cracking Test
   Australia-DSTO

2. Modified Gapped Bead on Plate Test
   Australia-DSTO

3. Modified WIC Test
   USA-NSWCCD

4. Measurement of K_{IEAC} for Higher Strength Steels
   USA-Army Benet Lab.-ARDEC

5. J-integral Fracture Toughness Test Procedures
   USA-Army Benet Lab.-ARDEC

6. Fatigue Life in Hydrogen Environments
   USA-Army Benet Lab.-ARDEC
   UK-Univ. of Cranfield

7. Survey Worst Case Scenario for Hydrogen Cracking During Fabrication
   Australia-DSTO
   Australia-ASC
   USA-NSWCCD

8. Develop Testing Criterion for Weld Repair
   Australia-DSTO
   Australia-ASC
   USA-NSWCCD

9. Modeling of Electronic Bonding of Hydrogen in the Zone Ahead of Sub-critical Cracks in Ferrous Alloys
   USA-Army ARL
   USA-CSM
   Australia-DSTO

10. Modified Cruciform Testing
    Australia – DSTO
    Australia – ASC
    USA-NSWCCD
    Canada-DREA

OPERATING ASSIGNMENT PTP1 - 013 (October 8, 1998)

HYDROGEN MANAGEMENT IN HIGH STRENGTH STEEL WELDMENTS FOR DEFENCE APPLICATIONS

Task 1 Research and Development of New Weld Metal Hydrogen Cracking Tests

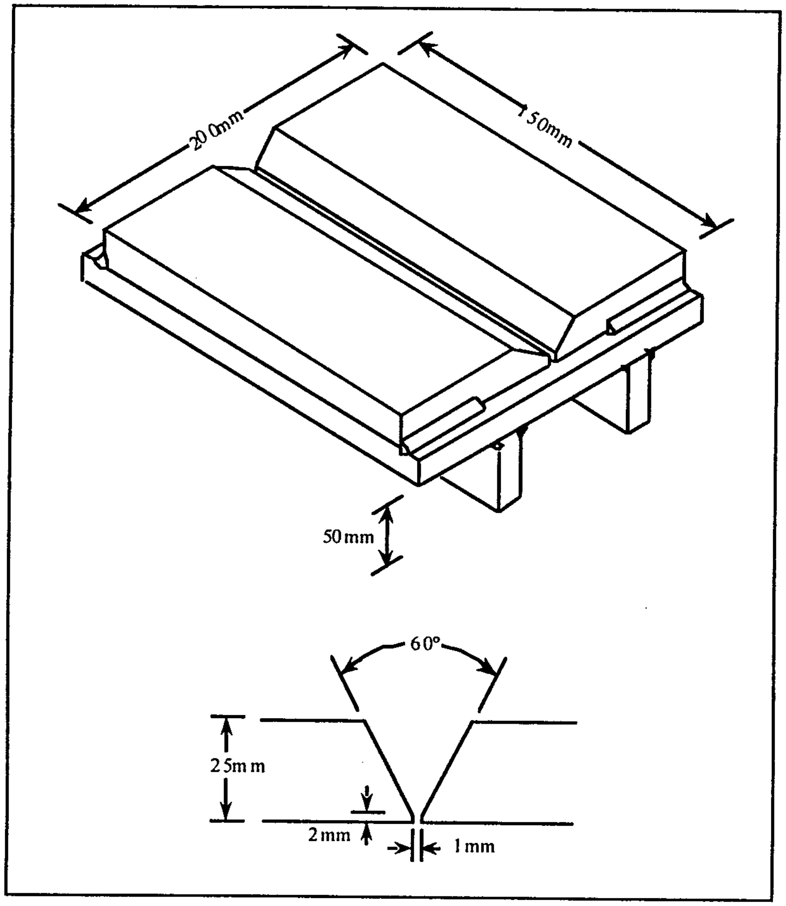
Activity	Status	Results	Description	Organization
1. Longitudinal Restraint Cracking Test	completed	LRC tests found to be unconservative	The longitudinal restraint cracking (LRC) test was found to be unconservative. Effort has been redirected from this activity to the NSWC modified cruciform test (see Task 1 Activity 3).	Aust. - DSTO
2. Modified Gapped Bead on Plate Test	completed	Modified GBOP test was found to be unconservative despite the quench modification.	Despite the use of a "quench" to limit the removal of hydrogen, the modified GOP test was found to be unconservative.	Aust. - DSTO
3. Modified WIC Test	completed	Modified WIC test was developed and evaluated. Modified test proved to be less severe than standard test.	WIC test was modified as follows: (1) increased plate thickness to 2" and modifying the joint design (to increase thermal severity) and (2) incorporated transverse notches (to assess propensity for transverse cracking). Results indicated that the 2" specimen was less severe than the standard specimen. Strain gage measurement suggested that the decreased severity were due to reduced restraint. We are determining whether other restraining schemes are feasible.	USA - NSWCCD
4. Measurement of K_{IEAC} for Higher Strength Steels	completed	Stage II hydrogen crack growth rates were approx. $1.1B^{-2}$, $2.3\ B^{-3}$ and $2.4\ E^{-2}$ mm/s. Crack growth rates increase by over four orders of magnitude for a 50% increase in yield strength.	K_{IEAC} tests were conducted on isothermally processed A723 steels at YS levels of 1275 Mpa and exhibited no significant difference in incubation times, crack growth rates, or K_{IEAC} threshold levels when compared to conventionally quenched and tempered A723 steels at identical YS levels. K_{IEAC} tests were conducted on quenched and tempered A723 Grade 2 steels at YS levels of 1130 Mpa, 1275 Mpa, 1330 Mpa, and 1380 Mpa. Hydrogen crack growth rates (da/dt) of the 1380 Mpa steel dramatically increased by approx. 1000 fold when compared to the 1130 Mpa steel.	USA - Army Benet Lab
5. J-integral fracture toughness test procedures	completed	Small specimen J-Integral bend test has been develop and evaluated.	A simplified ASTM J-Ic fracture toughness bend test has been developed for testing small specimens from welds. An electric potential drop method is available for automated tests of H-cracking threshold or H-affected fatigue crack growth. The effects of side-grooves, comp. and heat treat on J-Ic fracture toughness and cleavage behavior of steel is being measured.	USA - Army Benet Lab

Task 1 (continued) Research and Development of New Weld Metal Hydrogen Cracking Tests

Activity	Status	Results	Description	Organization
6. Fatigue life in hydrogen environments	in progress	Fatigue life test and analysis methods are being studied	A new life analysis procedure using a "fatigue intensity factor" clearly differentiates between mechanical and hydrogen cracking affected life of steel (cannon) components. This work is being conducted jointly with Prof. Parker (Univ. of Cranfield, UK). Causes of hydrogen cracking and control measures for cannon components are being identified, including thermal damage and associated residual stress effects on fatigue life.	USA - Army Benet Lab UK – Univ. of Cranfield
7. Survey worst case scenario for hydrogen cracking during fabrication	completed	From fabrication experience determined the design detail and working environment that represents the greatest risk of cracking	As a basis for determining the most appropriate test procedure, descriptions of worst case scenarios for hydrogen cracking in fabrication are being sought. The descriptions are to be circulated for comment. This activity has had involvement from the Australian Submarine Corporation's welding manager. However, he is no longer with the ASC. From experience with Collins fabrication, greatest risk is with closed tanks. Cruciform joint designs have high restraint and pose an increased risk. Most cracking occur at repairs.	Aust. - DSTO Aust. - ASC USA - NSWCCD
8. Develop testing criterion for weld repair	in progress	A reproducible test for measuring hydrogen crack sensitivity	Test piece design will incorporate a cruciform joint design. A groove of 100 to 150 mm lengths would be prepared at the crown of each weld. The groove depth should be half the throat thickness. Welding to fill the groove should be performed using candidate procedures.	Aust. – DSTO Aust. – ASC USA-NSW CCD Canada-DREA
9. Modeling of Electronic bonding of hydrogen in the zone ahead of sub-critical cracks in ferrous alloys	in progress	Application of new modeling approaches	Determine relative energies of interstitials to migrate into this zone. Characterize the intraplanar bonds when interstitials are present (eg. Establish if these interstitials change the nature of these bonds by promoting/hindering crack tip propagation in this zone).	USA – ARL USA – CSM Aust. - DSTO
10. Modified Cruciform Test	completed	Mod.cruciform test was found successful in detecting the propensity for long. and trans. crack. and weld metal embrittle. (via loss of duct. in all weld metal tensile specimens).	Design of a 50-mm thick modified cruciform specimen was performed. The major difference between the standard cruciform and the modified cruciform specimen is that the modified cruciform and longitudinal and transverse notches machined on the mating surface of the attached leg.	Aust. – DSTO Aust. – ASC USA-NSWCCD Canada-DREA

Task 1:	Hydrogen Cracking Tests
Activity 1:	The Longitudinal Restraint Cracking Test
Organization:	Australia-DSTO
Description:	The Longitudinal Restraint Cracking Test (LRC) has been applied experimentally as a multipass hydrogen cracking test.
Results:	The LRC was found to be unconservative. No cracks developed in LRC tests that were conducted under conditions that were known to produce transverse hydrogen cracks in full-scale multipass welds. Future work needs to consider increasing the length of the weld to increase the longitudinal residual stress.
Plans:	NA
Status:	completed
Completion:	1996, Q4

Longitudinal Restraint Cracking Test



Multipass test

Not sufficiently severe to produce cracking using low-carbon low-hydrogen consumables

Task 1: Hydrogen Cracking Tests

Activity 2: Modified Gapped Bead on Plate Test

Organization: Australia-DSTO

Description: The standard Gapped Bead on Plate (GBOP) test is known to be unconservative for determining safe welding parameters for multipass welding. Yield strength level stresses are developed in the weld metal of the GBOP test specimen, however, the hydrogen concentration of a single pass is less than that which accumulates in multipass welds. An attempt was therefore made to make the GBOP test conservative by immersing the test piece in ice water 30s after the welding was extinguished. The aim of the "quench" was to decrease the rate at which hydrogen could diffuse from the test weld. During laboratory scale preheat free welding tests only the first pass is preheat free. Thereafter the temperature of the small test piece is elevated by the previous pass or passes. Subsequent passes may then be deposited soon after the first, at an elevated interpass temperature or after the piece has cooled to some low pre-defined temperature. If time is allowed for the test piece to cool then hydrogen from earlier passes will have time to diffuse from the weld and the effects of hydrogen buildup will be reduced. If a pass is deposited soon after the previous pass then the previous pass will have effectively preheated the test piece and the test is not really a test of preheat free welding. While preheating by earlier passes will also occur in a full scale structure, the effect will be reduced by the greater heat sink offered by the surrounding parent metal.

Results: Despite the "quench" treatment the test was still found to be unconservative.

Plans: NA

Status: completed

Completion: 1995, Q3

Task 1: Hydrogen Cracking Tests

Activity 3: Modified WIC Test

Organization: USA-NSWCCD

Description: Research on the development of a new hydrogen cracking test by designing a modified WIC type test was performed. The major differences between present practice and the modified approach being investigated is that the modified approach will use thicker plate and a modified joint design to increase the thermal severity of the test. A test fixture was developed to restrain the specimen during the test. Previously the specimen was welded to a tee beam or a 50-mm thick plate. This work required additional work to remove and inspect the specimen.

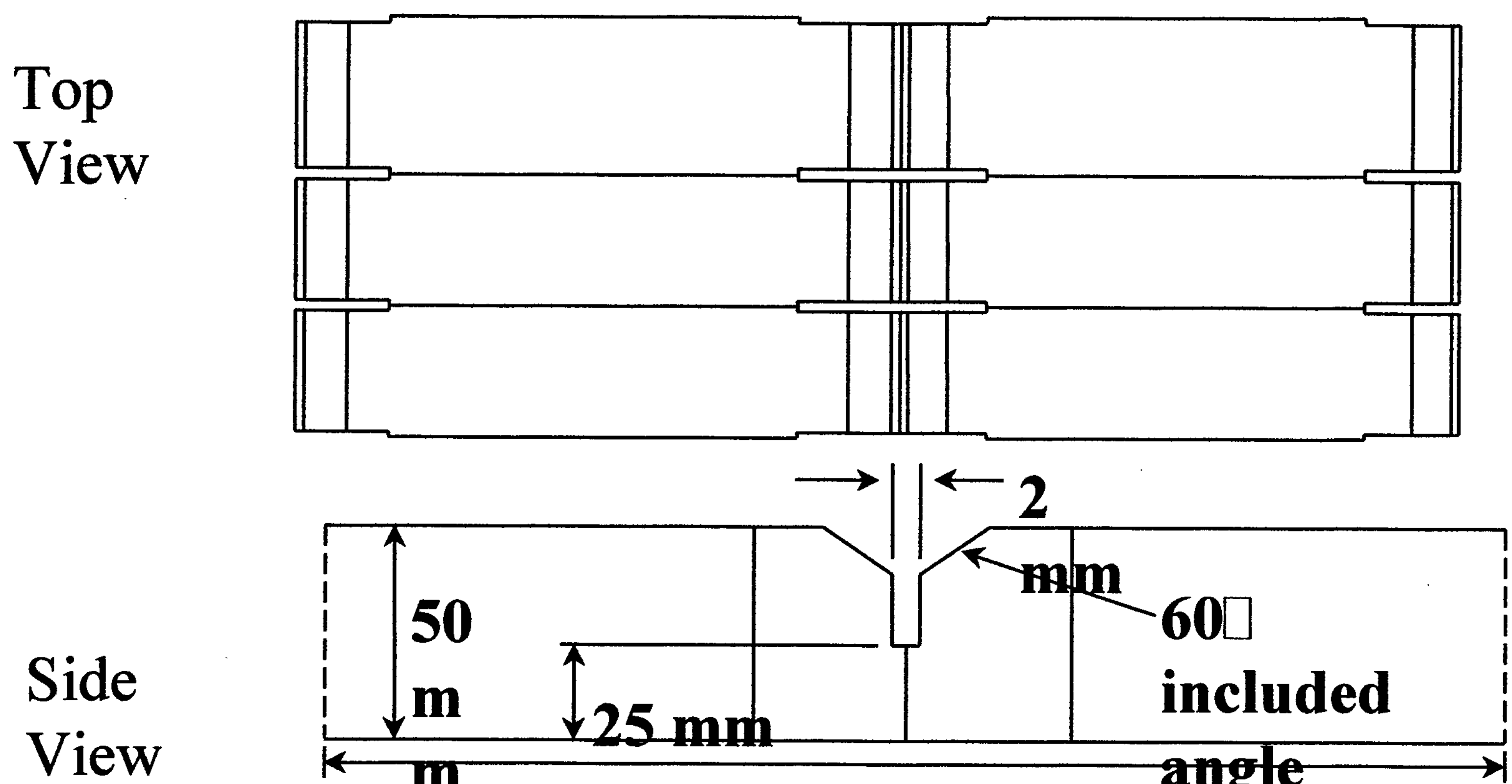
Results: The modified WIC test was developed and evaluated by NSWCCD. The modified test proved to be less severe than the standard test. The WIC test was modified as follows: (1) increasing the plate thickness to 50 mm, (2) modify the joint design by machining a land in the root of the weld to resist weld shrinkage stresses, (3) incorporating transverse notches (to assess propensity for transverse cracking). Results indicate the modified 50-mm specimen was less severe than the standard 19-mm specimen. Strain gage measurements indicate that the decreased severity was due to reduced restraint. This work was presented at the PRICM 3 Conference on 16 July 1998. A copy of this paper will be forwarded with the final TTCP report.

Plans: NA

Status: Completed

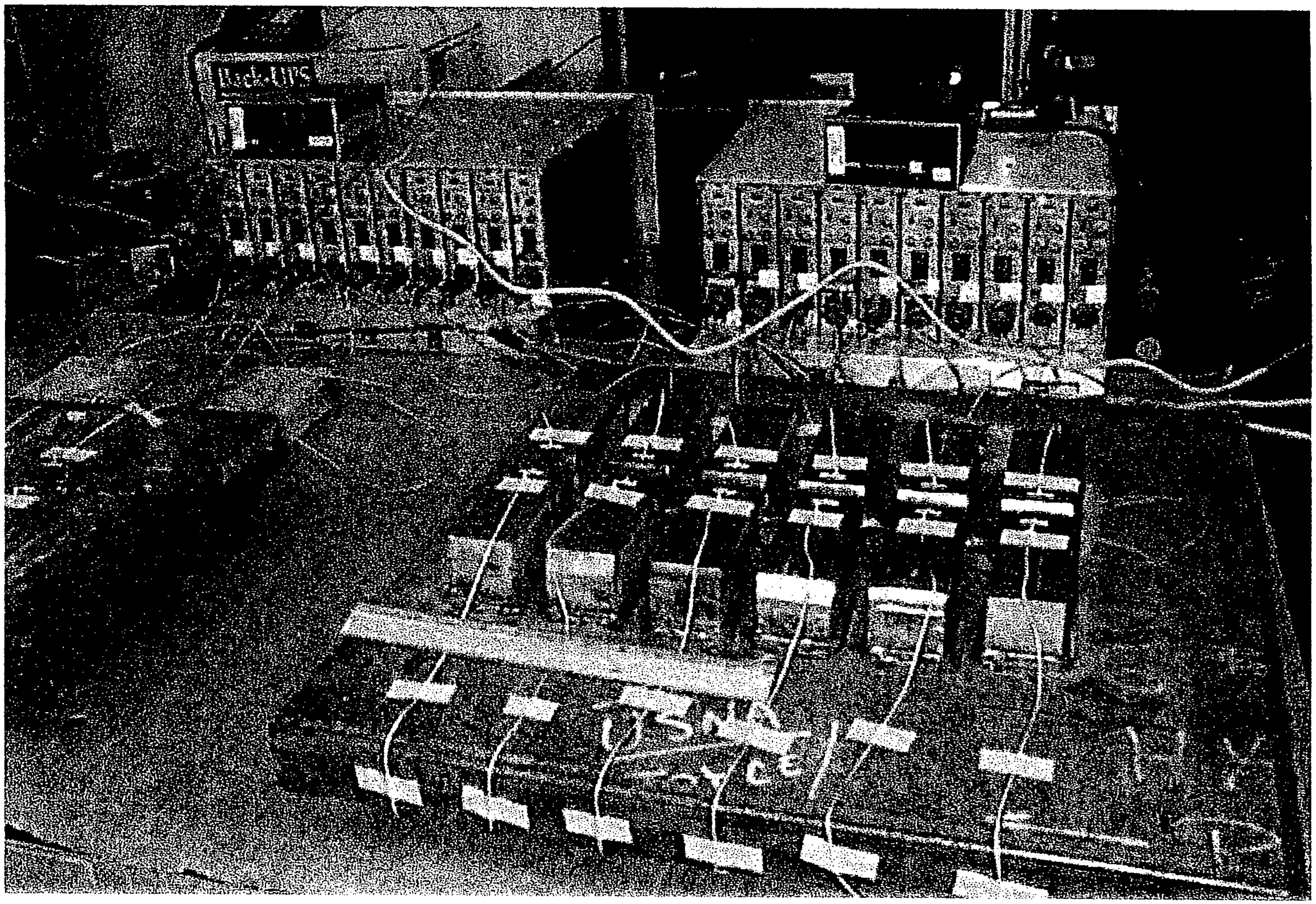
Completion: 1998, Q2

Modified WIC Specimen



Task 1, Activity 3, Modified WIC Test

Strain Gaged Modified WIC Specimens



Task 1, Activity 3, Modified WIC Test

Task 1: Hydrogen Cracking Tests

Activity 4: Measurement of K_{IEAC} for Higher Strength Steels

Organization: USA-Army Benet Laboratory-ARDEC [Vigilante, Underwood, Crayon]

Description: K_{Ieac} and da/dt tests were conducted on high strength steels. In-situ da/dt tests were conducted using the potential drop and an instrumented bolt technique.

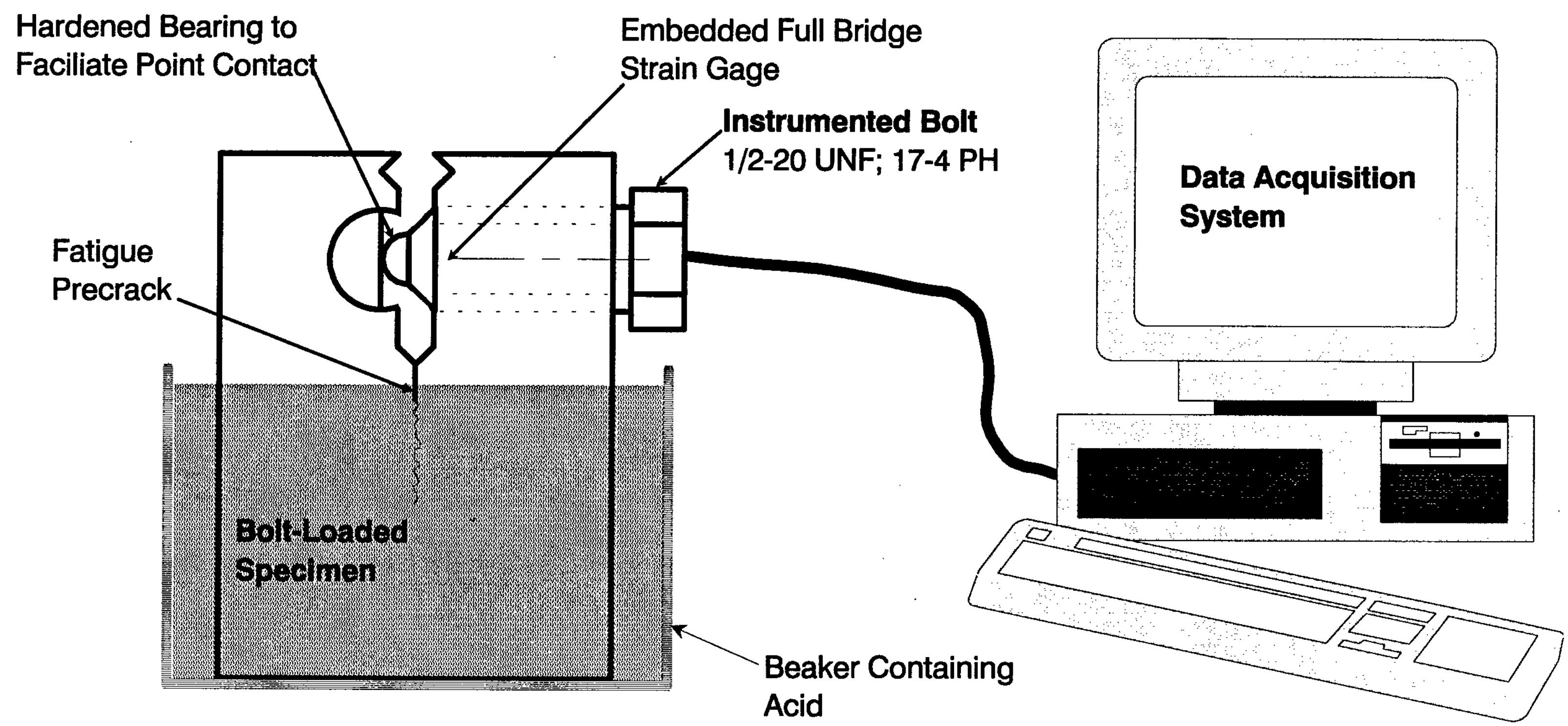
Results: K_{Ieac} and da/dt tests were conducted on AF141O, isothermal AF1410, and AerMet 100 using the constant displacement bolt-loaded specimen and the instrumented bolt technique. The instrumented bolt technique allows for in-situ hydrogen crack growth. The instrumented bolt is coupled to an automatic data acquisition system that monitors and records the load. From numerical expressions for the bolt-loaded specimen, the crack extension is computed from the drop in load. Stage II hydrogen crack growth rates were approximately 1. $1B^{-2}$, $2.3B^{-3}$, and $2.4E^{-2}$ mm/s, respectively. The effect of increasing yield strength on hydrogen crack growth rates is unmistakable. Crack growth rates increase by over four orders of magnitude for a *50%* increase in yield strength. This work was presented at the ASTM 30th National Symposium on Fatigue and Fracture Mechanics, St. Louis, MO, June 1998.

Plans: NA

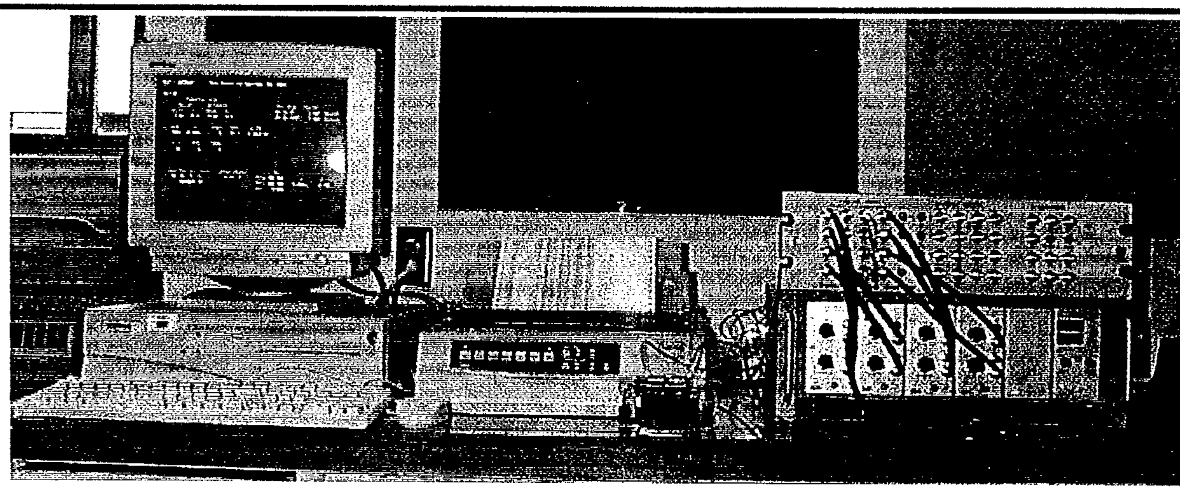
Status: Completed

Completion: 1998, Q2

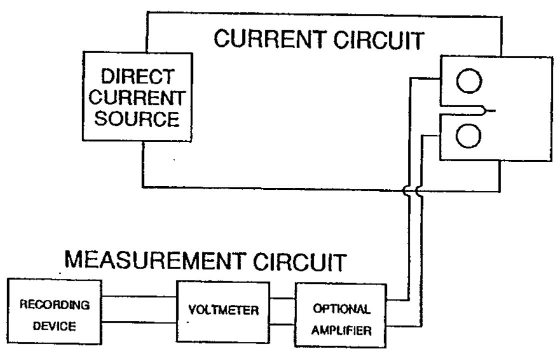
SCHEMATIC OF BOLT-LOADED SPECIMEN & INSTRUMENTED BOLT



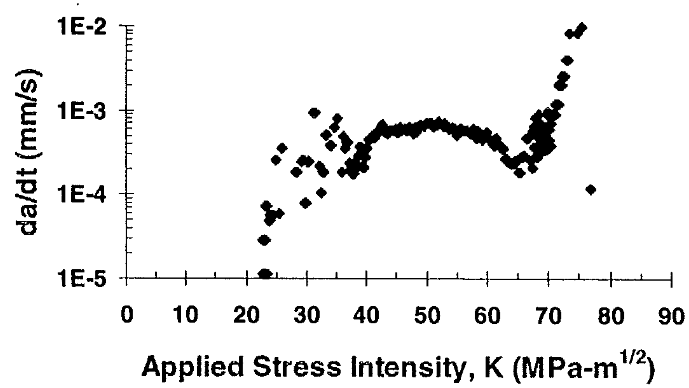
DIRECT CURRENT POTENTIAL DROP (DCPD)
IN-SITU CRACK MEASUREMENTS IN HYDROGEN ENVIRONMENTS



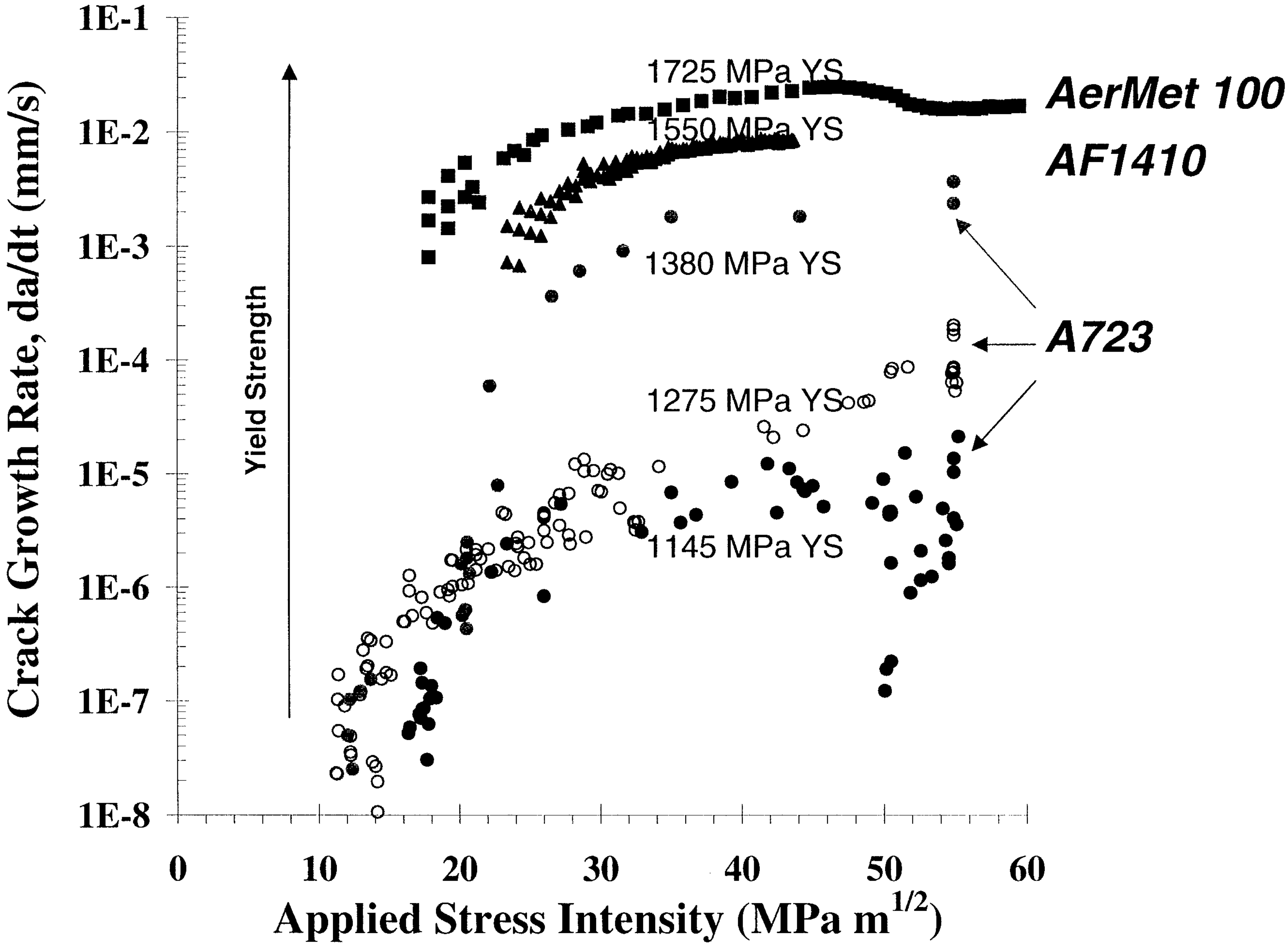
Benet Laboratories' Direct Current Potential Drop (DCPD) System



Schematic of DCPD System



Application of DCPD System to In-Situ Hydrogen Crack Growth Measurement in 4340 Steel



Crack Growth Rate, da/dt (mm/s)
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
Yield Strength
1725 MPa YS
1550 MPa YS
1380 MPa YS
1275 MPa YS
1145 MPa YS
AerMet 100
AF1410
A723
0
10
20
30
40
50
60
Applied Stress Intensity (MPa m^1/2)

Task 1: Hydrogen Cracking Tests

Activity 5: J-integral Fracture Toughness Test Procedures

Organization: USA-Army Benet Laboratory-ARDEC [Troiano]

Description: J-integral fracture toughness test procedures for weld applications are being investigated with emphasis on simplified test methods suitable for small specimens cut from welds. Measurements of J-Ic fracture toughness for cleavage in as welded 4130 steel HAZ have been made for applications to armament components.

Results: [a] A simplified ASTM J-Ic fracture toughness bend test has been developed for testing small specimens from welds; COMPLETED.

[b] An electric potential drop method is available for automated tests of hydrogen cracking threshold or hydrogen affected fatigue crack growth; COMPLETED.

[c] Effects of side-grooves, composition and heat treat on J-Ic fracture toughness and cleavage behavior of steel have been measured; COMPLETED.

Benet Laboratories modified the bolt-loaded specimen to test the hydrogen susceptibility of various coatings. Developed a FEA model of this modified geometry to accurately determine applied stress levels. Electroplated nickel was found to produce a good hydrogen barrier coating for high strength steels. This work will be presented at the 8th International Conference on Mechanical Behavior of Materials, Victoria, B.C., May 1999.

Plans: NA

Status: Completed

Completion: 1998, Q3

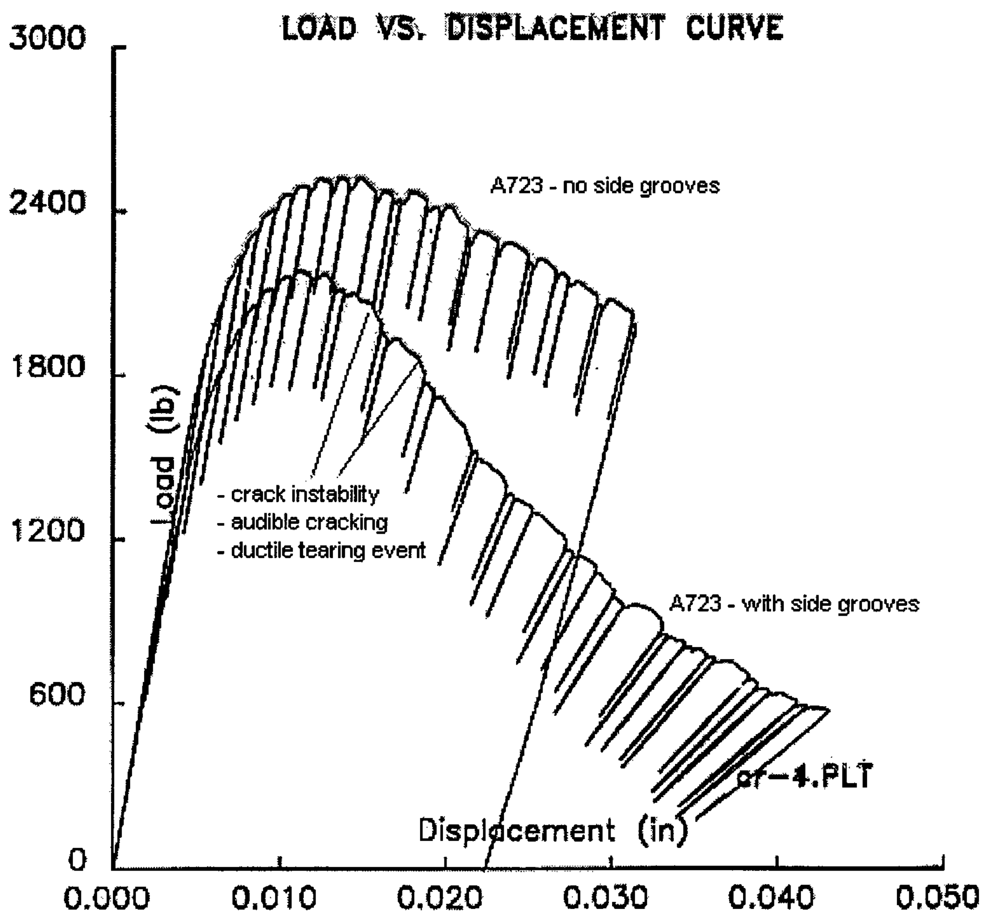
Task 1: Hydrogen Cracking Tests
Activity 5: J-integral Fracture Toughness Test Procedures

Description of following load-displacement plots:

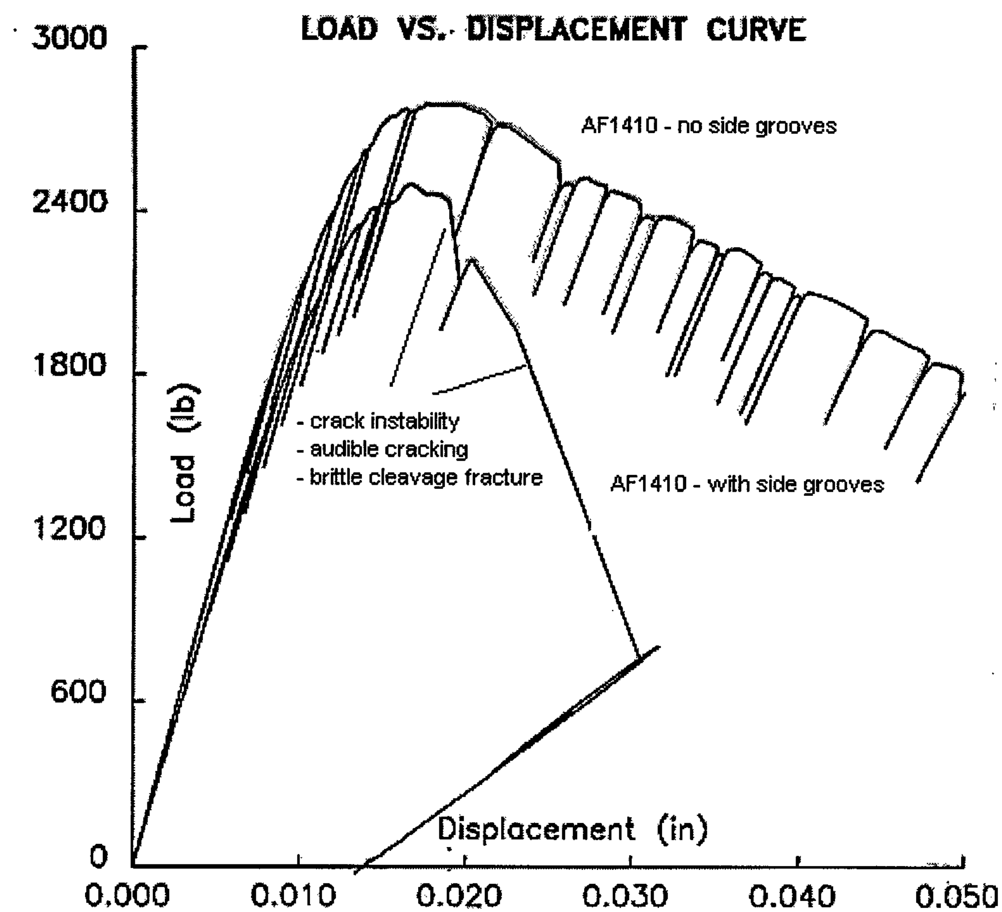
The following two load-displacement plot show some of the preliminary work we have performed in regards to evaluation of crack instability and cleavage events for high strength steels. The work presented here is preliminary and has not yet been published. We have observed a marked increase in toughness of A723 steel (YS-166 ksi) and AF1410 (YS-200 ksi) when tested without side grooving. This increase is the result of an increased plane stress zone on the specimen edges. You can see from the AF1410 plot that major cleavage event occurred in the side grooved specimen, at a load approximately 10% lower than the peak load of the non-side grooved specimen. These events are truly brittle cleavage events, and would go undetected had we not side grooved. In the A723 tests, an audible, rapid crack advance occurred in the side grooved specimen. Upon further investigation we discovered that the crack advancement was not brittle, but ductile tearing. We believe that this type of event is due to crack instability, and is highly dependent not only on the fact that the specimen is side grooved but also dependent on the size of the specimen.

This work is temporarily on hold because of lack of personnel in our laboratory. We anticipate that we will be able to resume this work around October, 1999. If our projected start date is accurate we anticipate that we will have final results around December 2000.

A723 Steel - Y.S. = 166 ksi



AF1410 - Y.S. = 190 ksi



Task 1: Hydrogen Cracking Tests

Activity 6: Fatigue Life Analysis in Hydrogen Environments

Organization: USA-Army Benet Laboratory-ARDEC [Underwood]
UK-Univ. of Cranfield

Description: A new analysis has been described for characterizing fatigue life, including local stresses and initial crack. This work is being conducted jointly with U. Parker (Univ. of Cranfield, U. K.).

Results: [a] A new fatigue life analysis procedure using a "fatigue intensity factor" clearly differentiates between mechanical and hydrogen cracking affected life of steel (cannon) components; COMPLETED; ICF9 (Sydney, 97), FD98 (Helsinki, 98).

[b] Causes of hydrogen cracking and control measures for heat affected cannon steels are being identified, including models of thermal residual stress and hydrogen cracking and their effect on fatigue life; IN PROCESS; ASME PVP (San Diego,98), ARO (Ottawa, 98); COMPLETED, 1999, Q3.

[c] Investigation of direct corrosion fatigue effects of hydrogen [from cannon combustion gasses] on fatigue life of high strength steels; INITIATED; completion 2000.

Plans: Causes of hydrogen cracking and control measures for cannon components are being identified, including thermal damage and associated residual stress effects on fatigue life.

Status: in progress

Completion: 2000, Q3

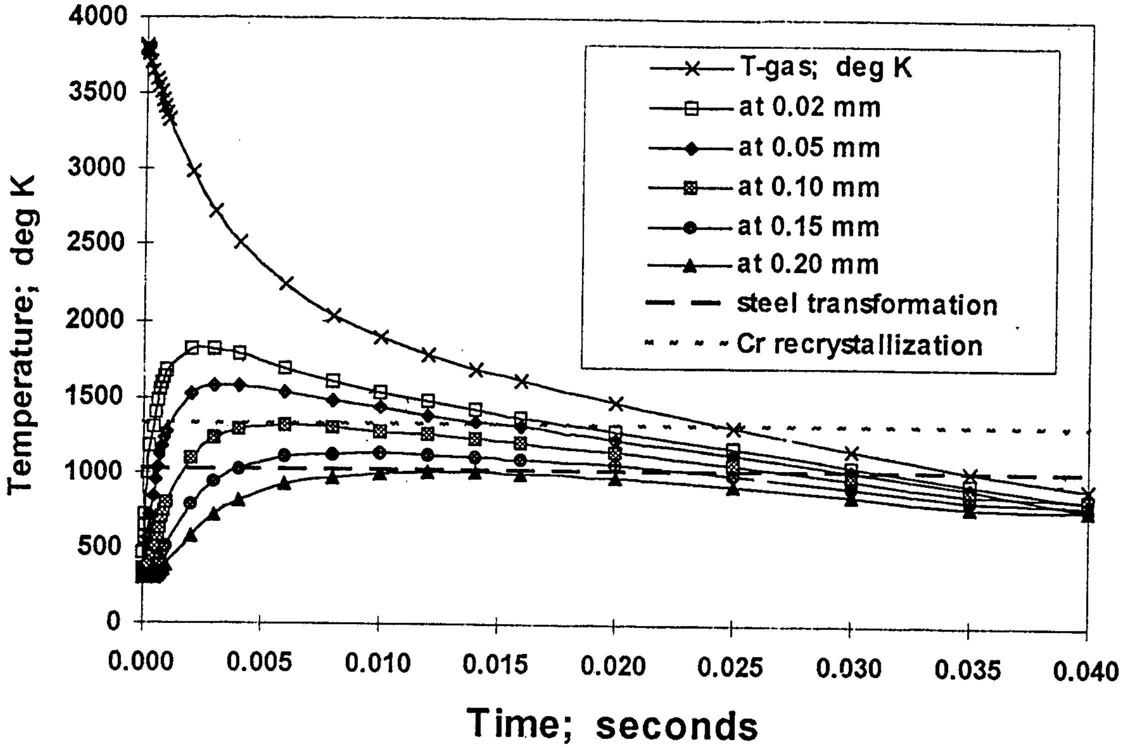


Figure 3 - *Temperature-Time-Depth Calculations for Near-Bore Region of Cannon A using 3820 K Maximum Gas Temperature*

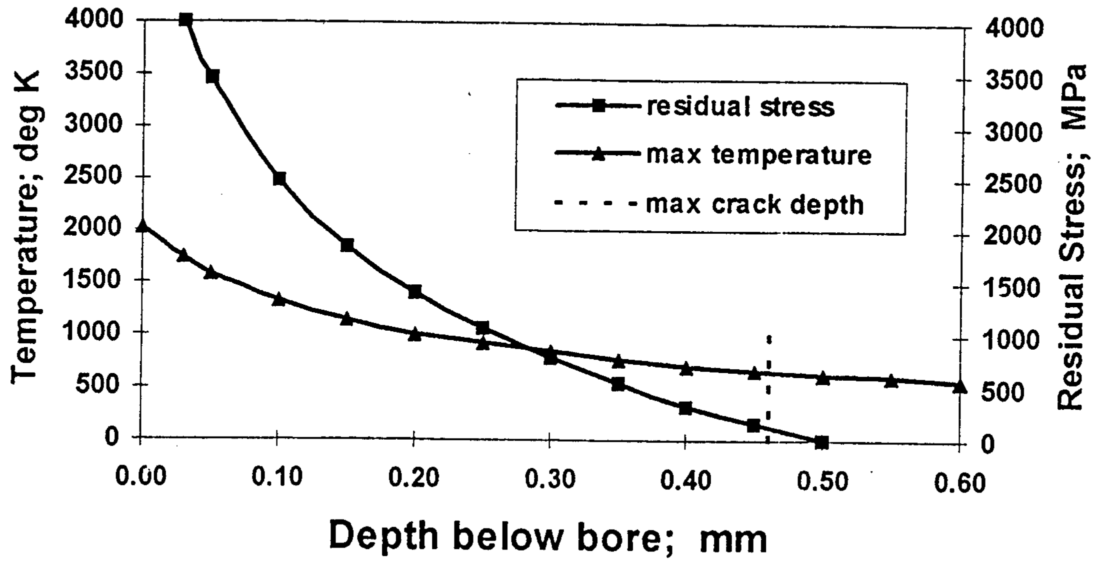


Figure 4 - *Maximum Temperature and Thermal Residual Stress Calculations for Cannon A using 3820 K Maximum Gas Temperature*

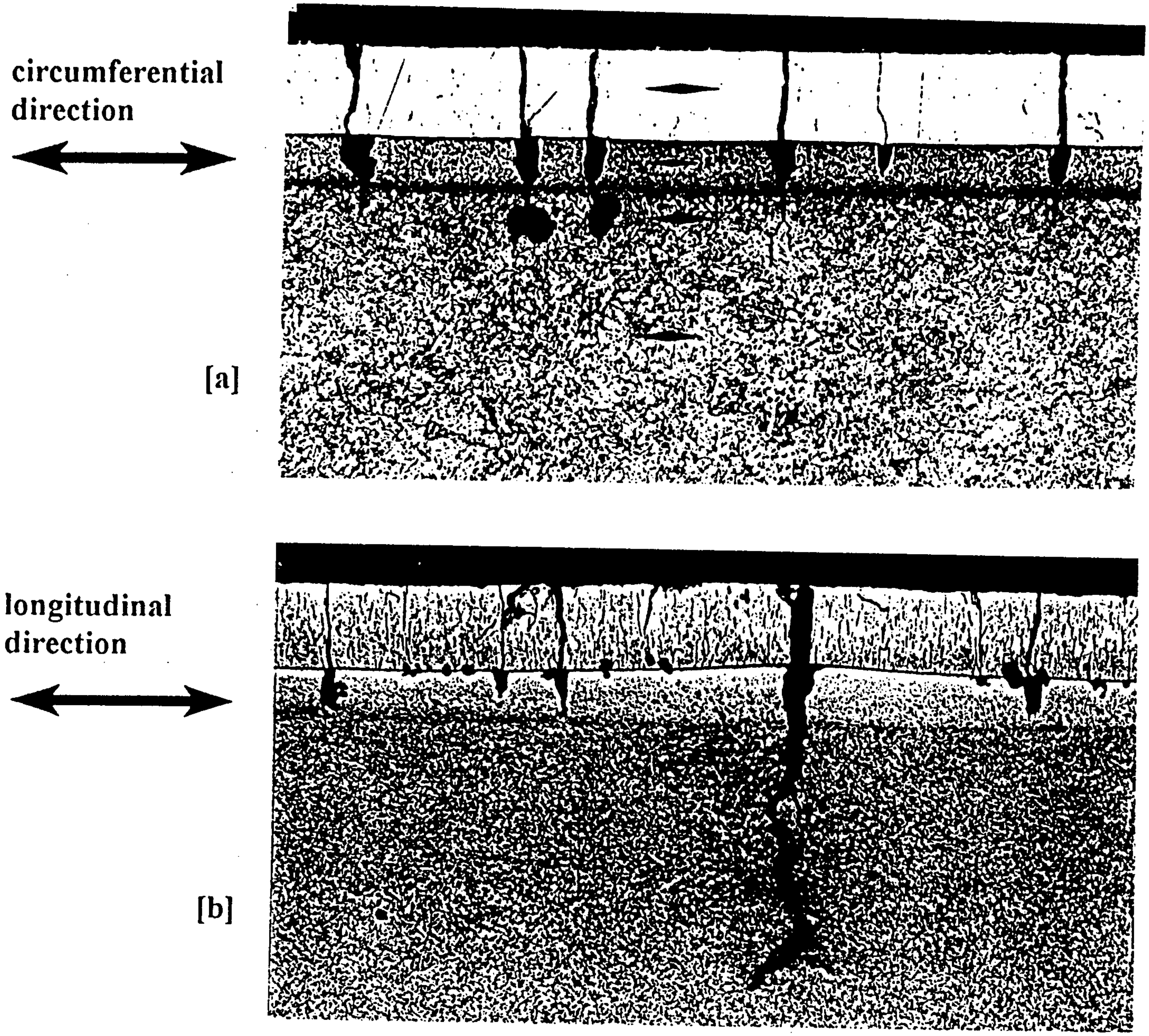


Figure 1 - *Polished and Etched Sections from Near-Bore Region of Cannon A Following 40 Firings, 100X; [a] section showing C-R cracks, the steel microstructure and microhardness indentations; [b] section showing L-R cracks and the chromium microstructure; Ref. [3]*

Task 1: Hydrogen Cracking Tests

Activity 7: Survey Worst Case Scenarios for Hydrogen Cracking During Fabrication

Organization: Australia-DSTO
Australia-ASC
USA-NSWCCD

Description: As a basis for determining the most appropriate test procedure, descriptions of worst case scenarios for hydrogen cracking during fabrication are being sought.

Results: The design detail and working environment that represents the greatest risk of cracking was determined from fabrication experience.

Plans: Descriptions are being requested and will be circulated for comment.

The survey for worst-case scenarios show that repair welding of high strength steel structures represents a "worst-case scenario". Cracking is commonly found in repair welds as these usually occur in regions of difficult access and high restraint. DTSO have reviewed ASC fabrication records and have shown that, with exception of weld repairs, the highest risk of cracking occurs in high restraint joints where preheat is maintained only for short times, such as in small repair welds, and where hand torches are used for preheating. The major joints, such as hull longitudinal seams, circumferential seams and frame-to-hull welds, may take several days to complete. In these welds, heat is maintained until welding is complete and, over these long heating times, hydrogen has sufficient time to diffuse out of the joint so that the hydrogen content in the final weld zone is reduced considerably.

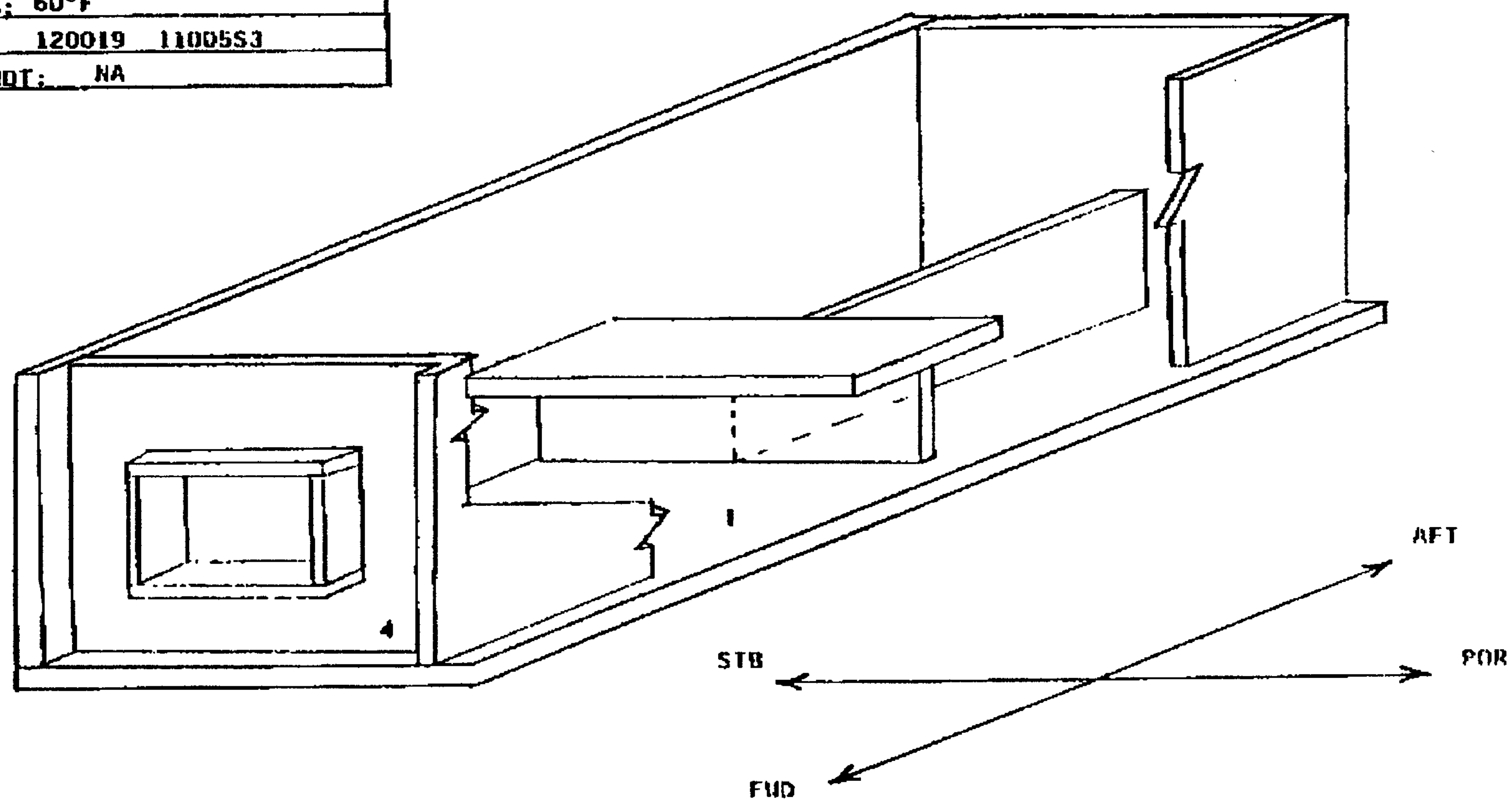
One area prone to cracking has been investigated in detail. The cracks which have been identified were at highly restrained locations in a ballast tank (see figure) and they often coincided with the end of weld runs.

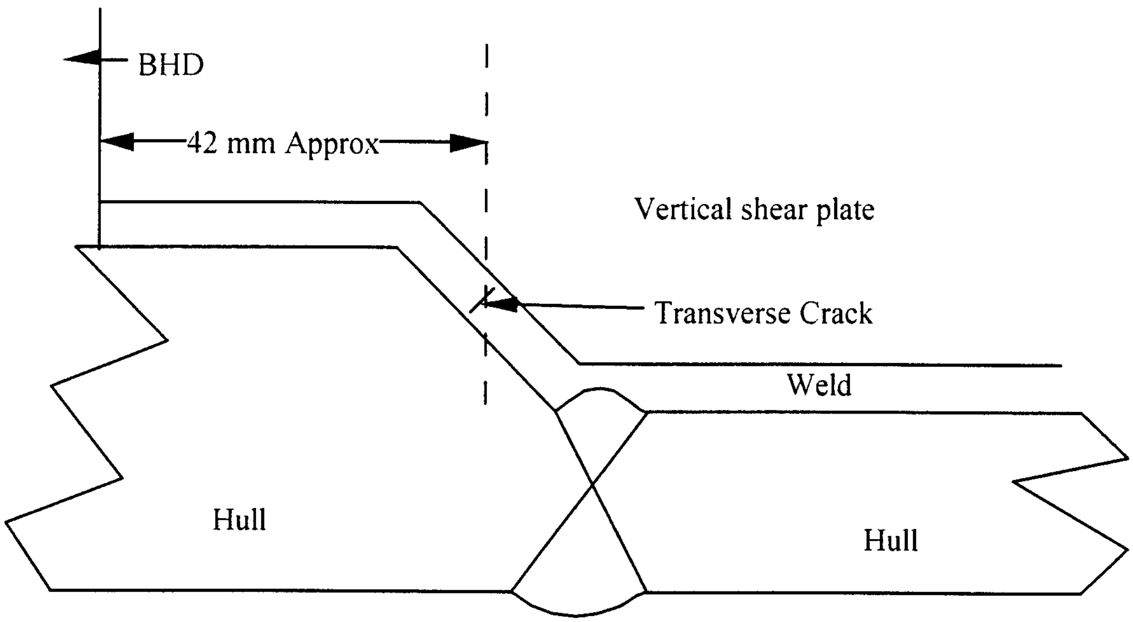
Status: Completed

Completion: 1998, Q4

Task 1, Activity 7, EB Small Scale Fabrication Model

JOINT #:	4-1
PROCESS:	GMAW SPRAY
POSITION:	HORIZONTAL
PREHEAT:	60°F
INTERPASS:	60°F
WIRE LOT:	120019 1100553
SPECIAL NDT:	NA




BHD
42 mm Approx
Vertical shear plate
Transverse Crack
Weld
Hull
Hull

Task 1: Hydrogen Cracking Tests

Activity 8: Development of Testing Criteria for Weld Repair

Organization: Australia-DSTO
Australia-ASC
USA-NSWCCD
Canada-DREA

Description: The progressive aging of existing Naval platforms has necessitated the development of hydrogen cracking tests for weld repair. This condition potentially represents a worst case scenario for hydrogen cracking susceptibility.

Results: A reproducible test for measuring hydrogen crack sensitivity.

Plans: Identify the worst case weld repair scenarios on Naval structures and develop a test plan which will evaluate the various hydrogen cracking testing procedures to assess these repairs. Suggested tests have been introduced for discussion.

Work at ASC has been stopped because the welding engineer who was developing test procedures is no longer employed there. The DSTO contribution to this work has also been deferred due to pressure of higher priority investigations. NSWC reports that Newport News and Electric Boat currently use the trough test as an in-house test for cracking. It is anticipated that it will take significant man-hours for the shipyards to come up with a good recommendation.

Status: in progress

Completion: 2001, Q4

Task 1: Hydrogen Cracking Tests

Activity 9: Modeling of Electronic Bonding of Hydrogen in the Zone Ahead of Sub-critical Crack in (BCC) Ferrous Alloys

Organization: USA-Army ARL
USA-CSM
Australia-DSTO

Description: This investigation will determine the relative energies of interstitials that can migrate to the zone of sub-critical crack in ferrous alloys. It will characterize the intra planar bonds when interstitials are present (e.g. establish if these interstitials change the nature of these bonds promoting/hindering crack tip propagation in the zone).

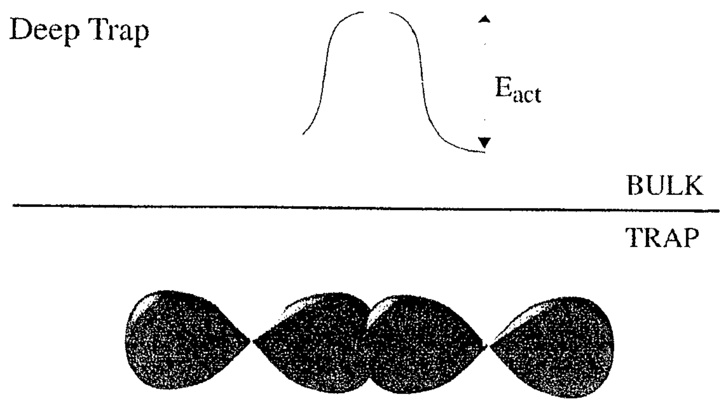
Results: There is evidence from prior calculations (CSM-Mark Eberhart) that much understanding can be determine as to the nature of hydrogen damage from these fundamental atomic scale calculations.

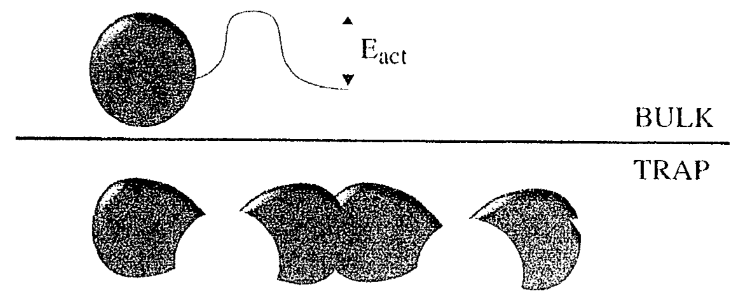
Plans: Establish a research team of internationally respected investigators, both theoretical and experimental scientists, and propose the scope and work statements for this project to be submitted to the appropriate funding agencies. Dr. Genrich Krasko, US Army Research Laboratory was proposed as primary Principal Investigator.

Status: in progress

Completion: 1999, Q2

Ab-initio Predictions of Hydrogen Trap Depths





- ab-initio calculations have shown that hydrogen trapping occurs at the bulk-trap interface.

- H s-orbitals overlap strongly where there is available trap election density across the interface giving rise to strong trap-H bonds.

- the effectiveness of the modeled materials as hydrogen traps decreases through the series:

CeO_2>TiC>Y_2O~>VC>NbC>Mo_2C

Task 1: Hydrogen Cracking Tests

Activity 10: Modified Cruciform Test

Organization: USA-NSWCCD
Australia-DSTO
Australia-ASC
Candada-DREA

Description: Design of a 50-mm thick modified cruciform specimen was performed. The major difference between the standard cruciform and the modified cruciform specimen is that the modified cruciform and longitudinal and transverse notches machined on the mating surface of the attached leg. In the standard specimen the mating surface is machined flat to minimize any gaps between the mating surfaces. Initial results of a 25-mm thick modified cruciform were successful in detecting the propensity for longitudinal and transverse cracking in multipass welds. Weld metal embrittlement was also assessed by evaluation of all weld metal tensile specimens removed from quadrants 3 and 4 of the cruciform specimen. The modified cruciform specimen thickness was increased to 50 mm to increase thermal severity when using no preheat and to increase the number of welding passes in each quadrant which may increase restraint severity.

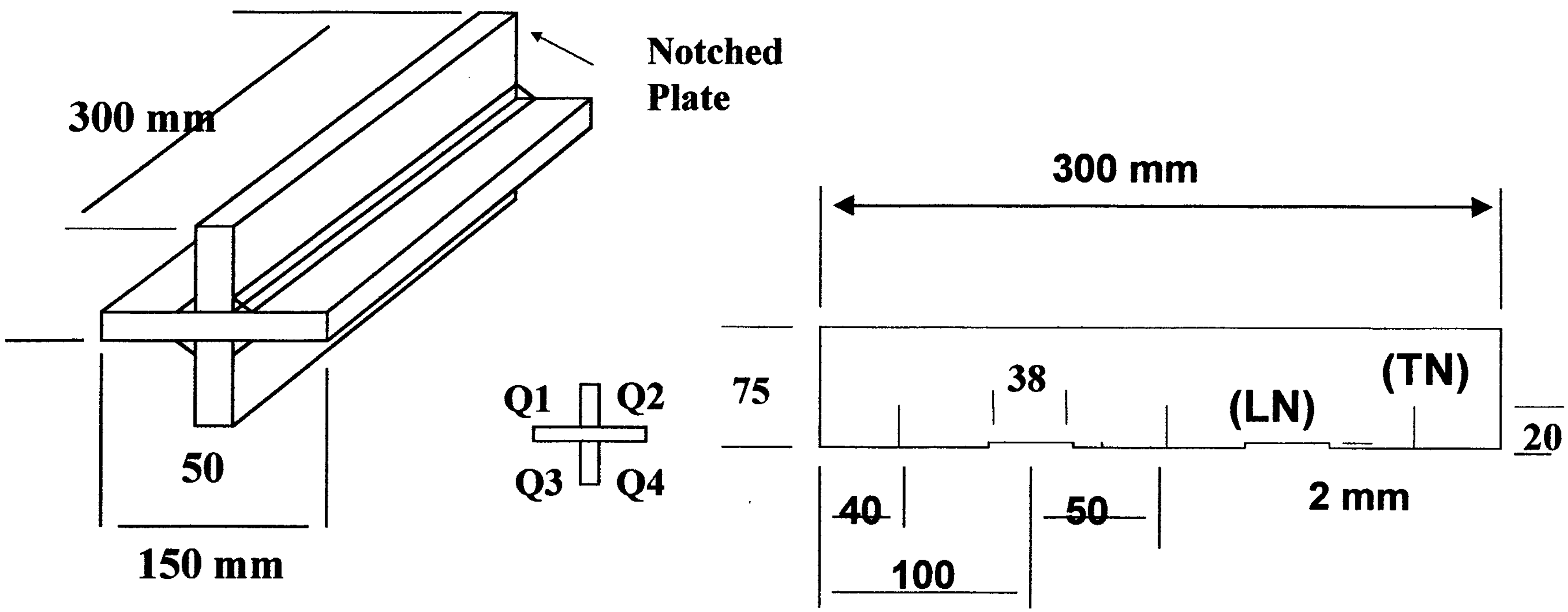
Results: The modified cruciform test has been found successful in detecting the propensity for longitudinal and transverse cracking and weld metal embrittlement (via loss of ductility in all weld metal tensile specimens). Thermal severity was more severe in the 50 mm thick specimen compared to the 25 mm thick specimen when no preheat is used. The results of the 50-mm thick modified cruciform tests were consistent with previously established cracking data based on single pass WIC tests and multiple pass 25-mm thick modified cruciform tests. A document describing the modified cruciform using the AWS B.4 format was prepared.

Plans: NA

Status: Completed

Completion: 1998, Q2

Modified Cruciform Specimen

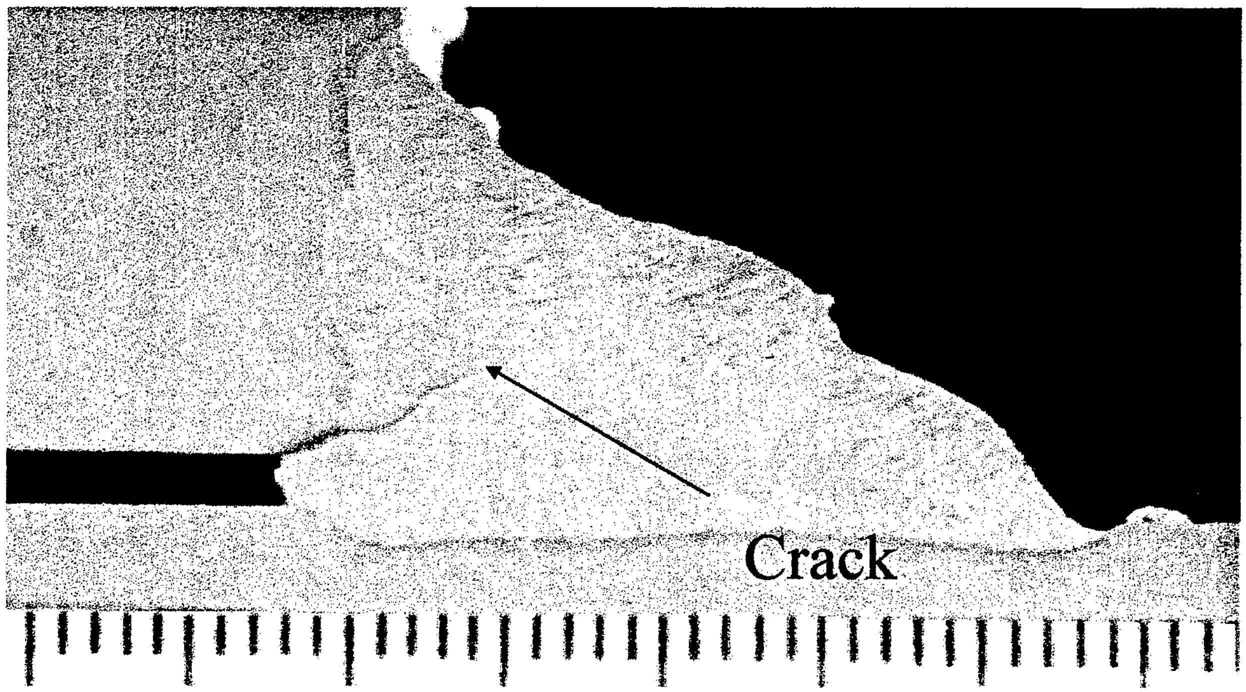


(TN) = Transverse Notch

Task 1, Activity 10, Modified Cruciform Test

MC-100 Weld Metal Cracking in the Modified Cruciform Test

HAZ
324
DPH



Weld
295-352
DPH

Specimen W377A

5 mm

Task 1, Activity 10, Modified Cruciform Test

4.2 TASK 2

Determination of the Relationship Between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

TASK 2

DETERMINATION OF THE RELATIONSHIP BETWEEN WELDING PARAMETERS (INCLUDING HYDROGEN CONTENT) ON MULTIPLE PASS WELD TRANSVERSE CRACKING

1. Hydrogen Induced Subcritical Cracking
   Australia-DSTO

2. Hydrogen Cracking and Heat Input
   Australia-DSTO

3. Risk Evaluation of Hydrogen Cracking
   Australia-DSTO

4. Hydrogen Arc Sensing and Modeling to Predict Weld Metal Hydrogen Content
   USA-NSWCCD
   USA-Penn. State Univ.

5. Modeling of Hydrogen Cracking Behavior in a Repair Weld
   Canada-DREA

6. Eliminate Post Weld Heat Treatment by an Electrotransport Practice
   USA-CSM

7. Characterization of Undermatched Weldments
   USA-NSWCCD
   Australia-DSTO
   Canada-DREA

8. Cracking Mapping in a T-Butt Joint
   Australia-DSTO
   USA-NSWCCD
   Canada-DREA

9. Hydrogen Contents in Multipass Welds
   UK-DERA
   Canada-DREA
   USA-NSWCCD
   Australia-DSTO

Task 2 Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity	Status	Results	Description	Organization
1. Hydrogen –induced subcritical cracking	in progress	Specimens have been prepared and preliminary test have been undertaken with new test rig.	An experimental technique has been developed to determine the relationship between the hydrogen sub-critical growth rate and both the microstructural constituents and diffusible hydrogen contents.	Aust. - DSTO
2. Hydrogen cracking and heat input	in progress	High heat input welds crack at lower 'critical hardness' levels than lower heat input welds.	A test matrix was conducted to determine the effect of heat input on hydrogen induced cracking. It was found that the resistance to hydrogen induced cracking is higher at higher heat input but that at high HI and low preheat HIC may occur in weld metal with moderately low hardness levels.	Aust. - DSTO
3. Risk evaluation of hydrogen cracking	completed	No significant evidence of cracking	An experimental test section was welded using a wide range of welding techniques and procedures. Little evidence of cracking was found.	Aust. - DSTO
4. Hydrogen arc sensing and modeling to predict weld metal hydrogen content	completed	Model is being developed to allow prediction of weld metal hydrogen content	The arc-sensing model will be extended to determine weld pool shape and time-temperature profiles associated with GMA welding. Currently, relationships between weld metal microstructures and toughness are being established. Hydrogen distribution and migration from the welding plasma to the solidified weld metal is being modeled. The model is being developed for GMA welding and will incorporate feed metal and resulting papilla characteristic of GMAW. The model utilized spectrographic data supplied by the hydrogen sensor to establish the initial hydrogen species in the plasma.	USA – NSWCCD USA – Penn. State Univ.

Task 2 (cont.) Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity	Status	Results	Description	Organization
5. Modeling of hydrogen cracking behavior in a repair weld	in progress	Basis for current recomm. and the docum. Of factors considered in develop. Practices for new steels used in Naval Construction (e.g. X-80, HSLA 65) and new welding practice and consumables.	The time delay a structure is inspected for hydrogen cracking has important implications for production efficiency and cost effectiveness. This especially true in repair welding, where a quick turnaround is essential to maximize ship availability and minimize total repair costs. These same repair scenarios impose a fairly high risk of hydrogen cracking risk relative to new building. This being so it is important that a reasonable delay times be used prior to inspection for hydrogen cracking, when such inspections are deemed to be required.	Canada - DREA
6. Eliminate Post weld heat treatment by a electrotransport practice	completed	with use of homopolar generator it may be possible to treat thick section materials	The concept of using electrotransport to reduce diffusible hydrogen levels was evaluated using transport calculations. The application of electrotransport during the welding thermal cycle maybe useful in reducing hydrogen cracking susceptibility in large structural components. Discussions in progress with the electromechanics laboratory of Univ. of Texas.	USA - CSM
7. Characterization of undermatched weldments	in progress	Potential for reduction or elimination of preheat	The use of undermatching weld metal may improve productivity of welding high strength steels by reduction or elimination of preheat	USA - NSWCCD Aust. DSTO Canada-DREA
8. Crack Mapping in a T-butt joint	in progress	Serial 'sections' through a T-butt joint to map crack locations in the weld and HAZ	A T-butt joint was welded using conditions known to produce HIC. Three-dimensional cracking frequency is measured throughout the joint by milling down through the joint and inspecting at 2mm intervals.	Aust. – DSTO USA-NSWCCD Canada-DREA
9. Hydrogen Content in Multipass Welds	in progress	Extension of work to understand weld hydrogen content	Determination of the influence of multiple thermal experiences due to multipass welding on the resulting diffusible hydrogen content.	UK – DERA USA – NSWCCD Aust. – DSTO Canada - DREA

Task 2: Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity 1: The Relationship Between Hydrogen Content and The Susceptibility to Hydrogen Cracking

Organization: Australia-DSTO

Description: An experimental technique has been developed to determine the relationship between the hydrogen induced sub-critical crack growth rate and both the microstructural constituents and diffusible hydrogen content.

Results: Specimens have been prepared and preliminary tests have been undertaken to determine charging times required to impart sufficient hydrogen to the test specimen to produce subcritical crack growth.

A test rig for conducting three point bend tests have been designed and assembled for the purpose of measuring subcritical crack growth rates in hydrogen charged specimens. Specimens of LTEC 120S weld metal have been charge electrolytically with hydrogen and subsequently tested for HIC. Subcritical crack growth has been detected. Preliminary calculations indicate a substantial drop in critical stress intensity factor for cracking because of hydrogen of hydrogen charging (K=48.5 Mpa/m2 as compared to K>200 Mpa/m2 in uncharged material). Examination of fracture surfaces has revealed intergranular cracking commonly associated with HIC. Further testing is in progress to calibrate/modify the test machine for quantitative measurement of crack growth rate and stress intensity factors. A range of specimens have been prepared, including preheat free weld metal.

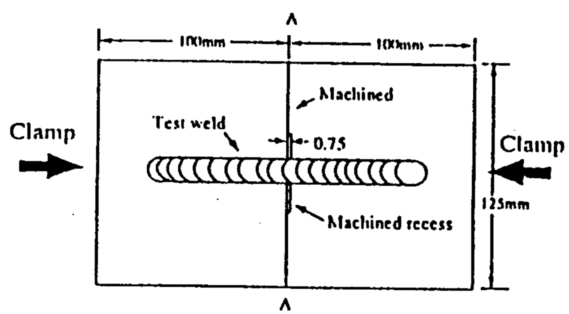
Plans: Continuing work in this activity will quantify the relationship between the bulk diffusible hydrogen content and the nature of the relationship between the bulk diffusible hydrogen content and the onset of cracking. Examination of microstructure and fracture surface is planned to gain a better understanding of the relationship between microstructure and the susceptibility to HIC.

Status: in progress

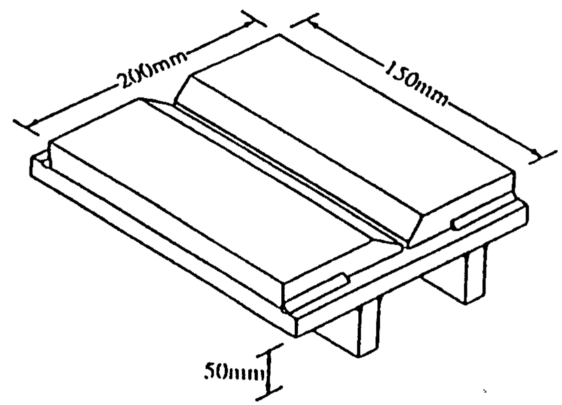
Completion: 2001, Q3

- ✗ Known Stress Intensity
- ✗ Known Hydrogen Concentration
- ✗ Constant Microstructure

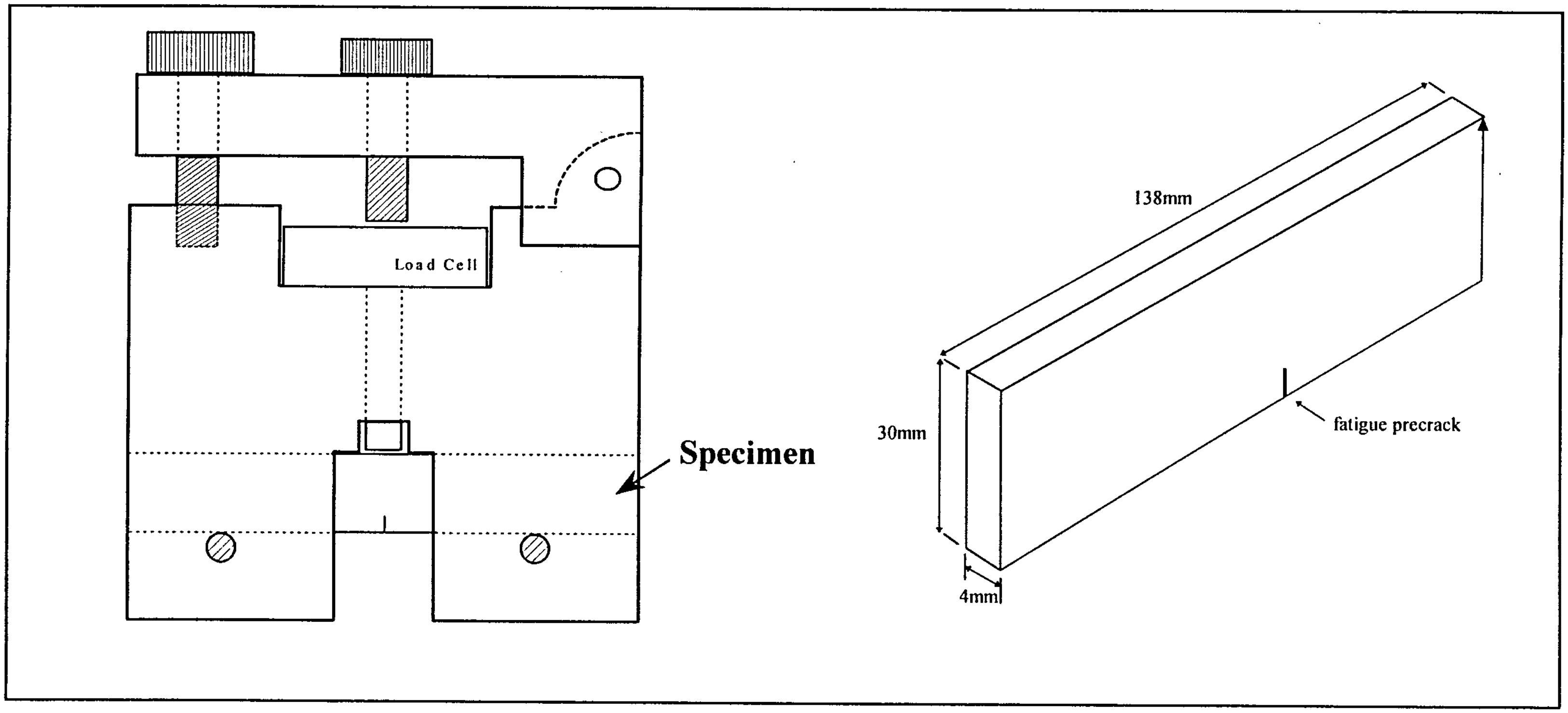
Gapped Bead on Plate



Longitudinal Restraint Cracking



Controlled Cracking Test



Task 2: Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity 2: Hydrogen Cracking and Heat Input

Organization: Australia-DSTO

Description: The influence of heat input on hydrogen cracking has been investigated for a submerged arc consumable using the Gapped Bead on Plate test. Test results indicate that although increased heat input was found to reduce the likelihood of hydrogen induced cracking, as expected, the high heat input welds were found to crack at lower "critical hardness" levels than lower heat input welds.

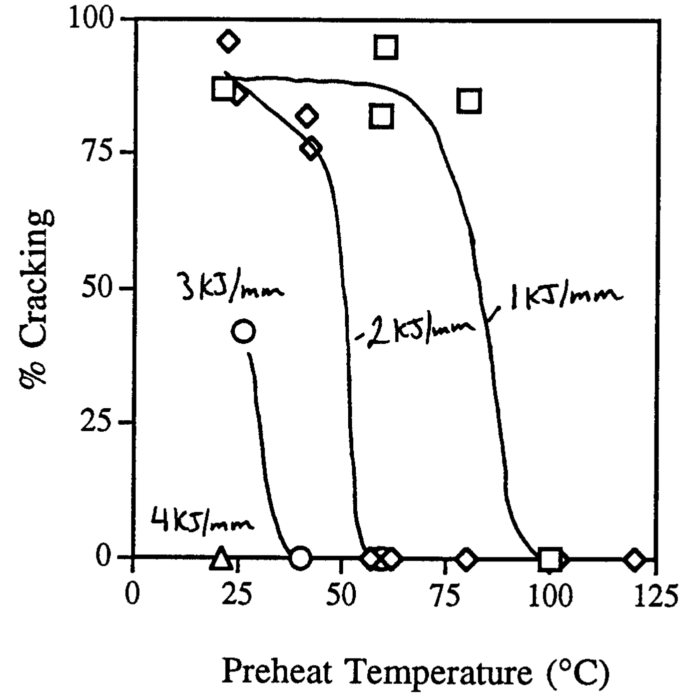
This result highlights the difficulties associated with measuring the influence of welding parameters and hydrogen content due to the interrelationship between the welding parameters and resulting microstructure, hardness, residual stress, and the weld hydrogen level. Because of these complex interrelationships, a controlled single variable cracking test has been developed and is being used to directly measure the inherent susceptibility of weld metal to hydrogen without the complications that normally arise in welding tests.

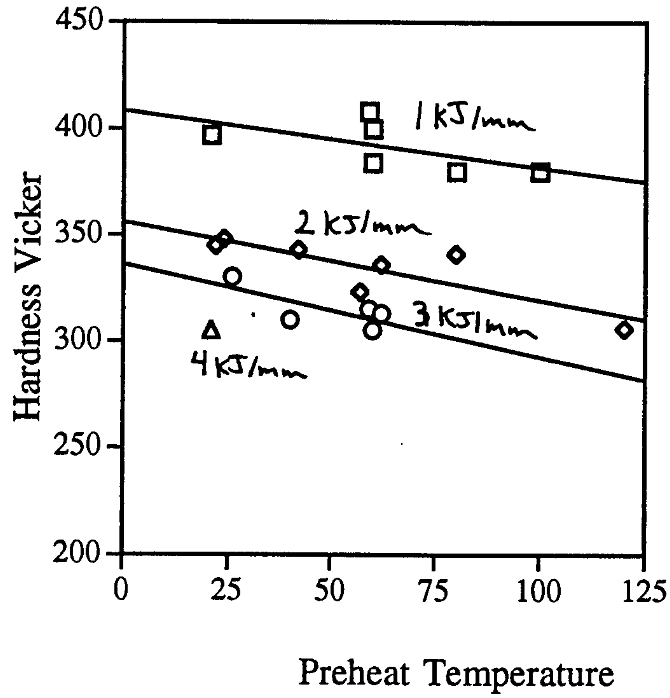
Results: High heat input welds crack at lower 'critical hardness' levels than lower heat input welds.

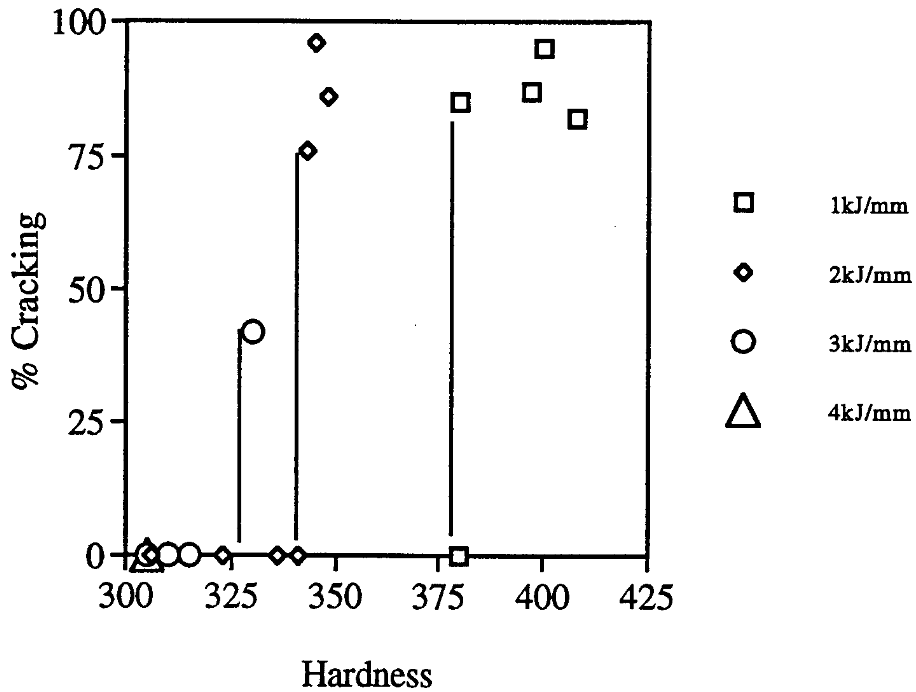
Plans: work continuing

Status: in progress

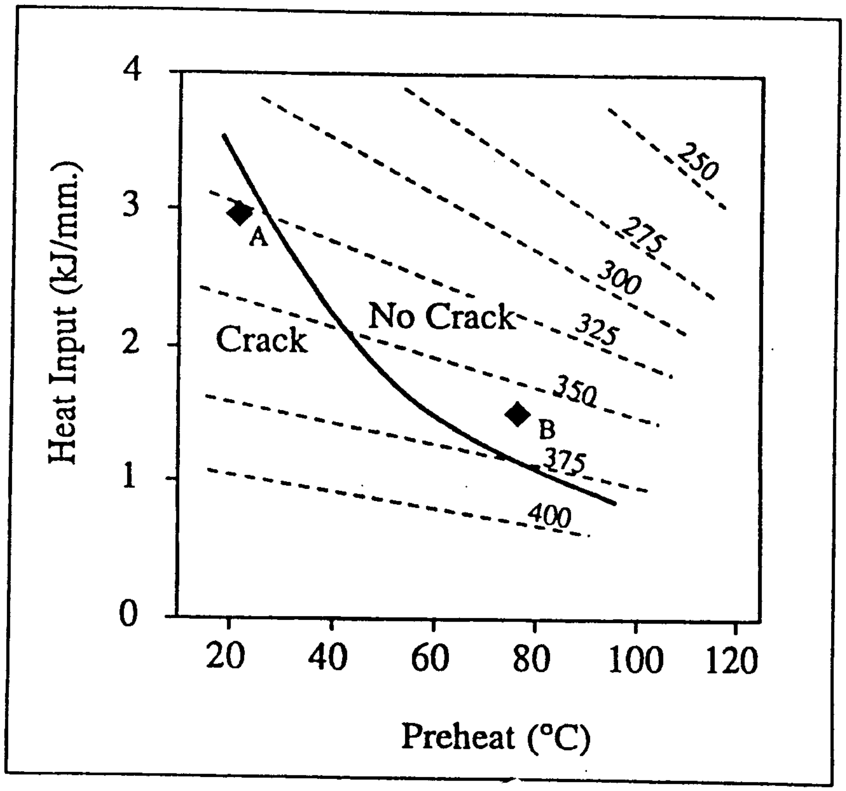
Completion: 2001, Q3


100
75
50
25
0
% Cracking
3KJ/mm
2KJ/mm
1KJ/mm
4KJ/mm
0
25
50
75
100
125
Preheat Temperature (°C)


450
400
350
300
250
200
Hardness Vicker
1KJ/mm
2KJ/mm
3KJ/mm
4KJ/mm
0
25
50
75
100
125
Preheat Temperature


100
75
50
25
0
% Cracking
300
325
350
375
400
425
Hardness
1kJ/mm
2kJ/mm
3kJ/mm
4kJ/mm

Cracking and Hardness As Functions of Welding Parameters



- "A" HV=330

  "B" HV=360

- Cracking occurs at "A" but not at "B"

Task 2:	Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking
Activity 3:	Risk Evaluation of Hydrogen Cracking
Organization:	Australia-DSTO

Description: Control of weld metal hydrogen cracking in high yield strength steel for submarine construction is an essential requirement. To evaluate the risk of hydrogen cracking and embrittlement, an experimental submarine section (7.8 m diameter, 2.4 m long, containing five stiffening ring frames) was fabricated using "high" carbon equivalent electrodes (Pcm= 0.283 versus typical values of 0.26) and a wide range of welding procedures. The effect of carbon content on cracking risk was also examined. The welds were examined both non-destructively and destructively.

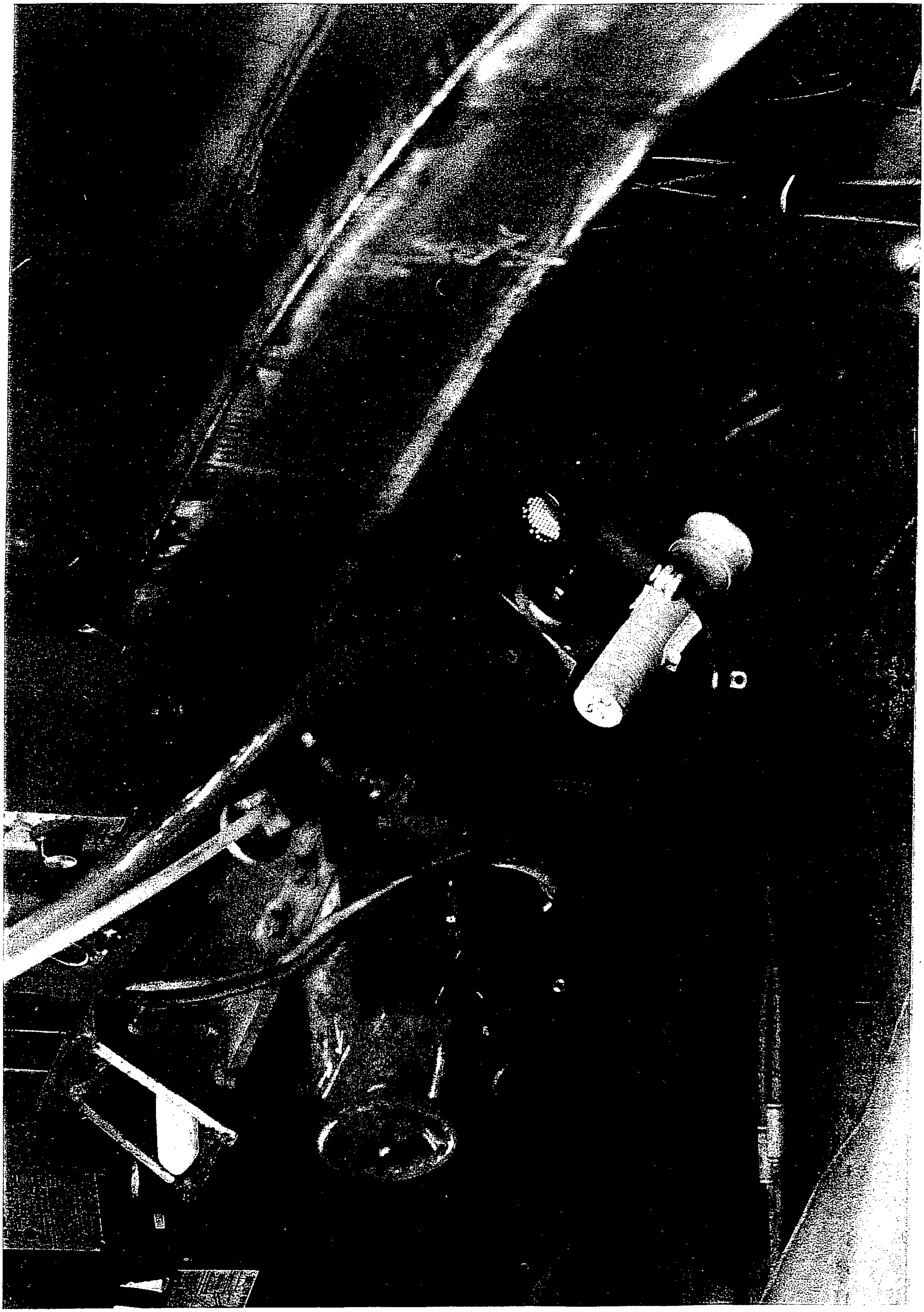
Results: No significant evidence of cracking was found. An increase in carbon content from 0.07 to 0.10 wt. pct. was found to have little effect on yield stress. Assessment of welds in a test fabrication showed that a wide range of techniques and procedures could be used without a risk of cracking.

In a separate program of work, the welding preheat and interpass temperatures in a cruciform joint were progressively reduced until the onset of cracking occurred. For MMA (SMA) welds and standard welding procedures, the preheat and interpass temperatures could be reduced to below 60 C without cracking. For SA welds, cracking occurred at 80 C preheat and interpass temperature. The time between weld passes was not measured during this work.

Plans: NA

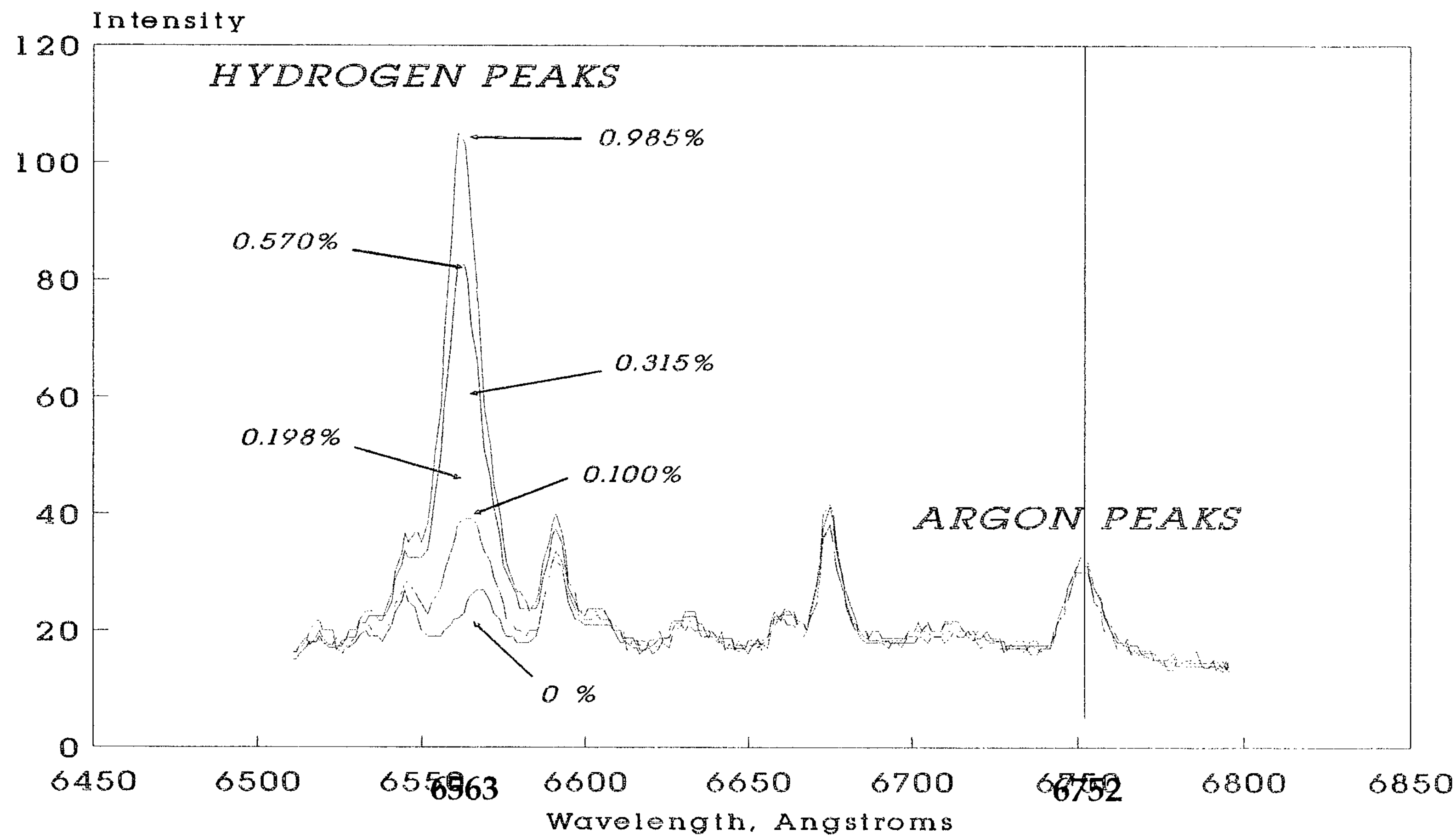
Status: completed

Completion: 1995, Q2



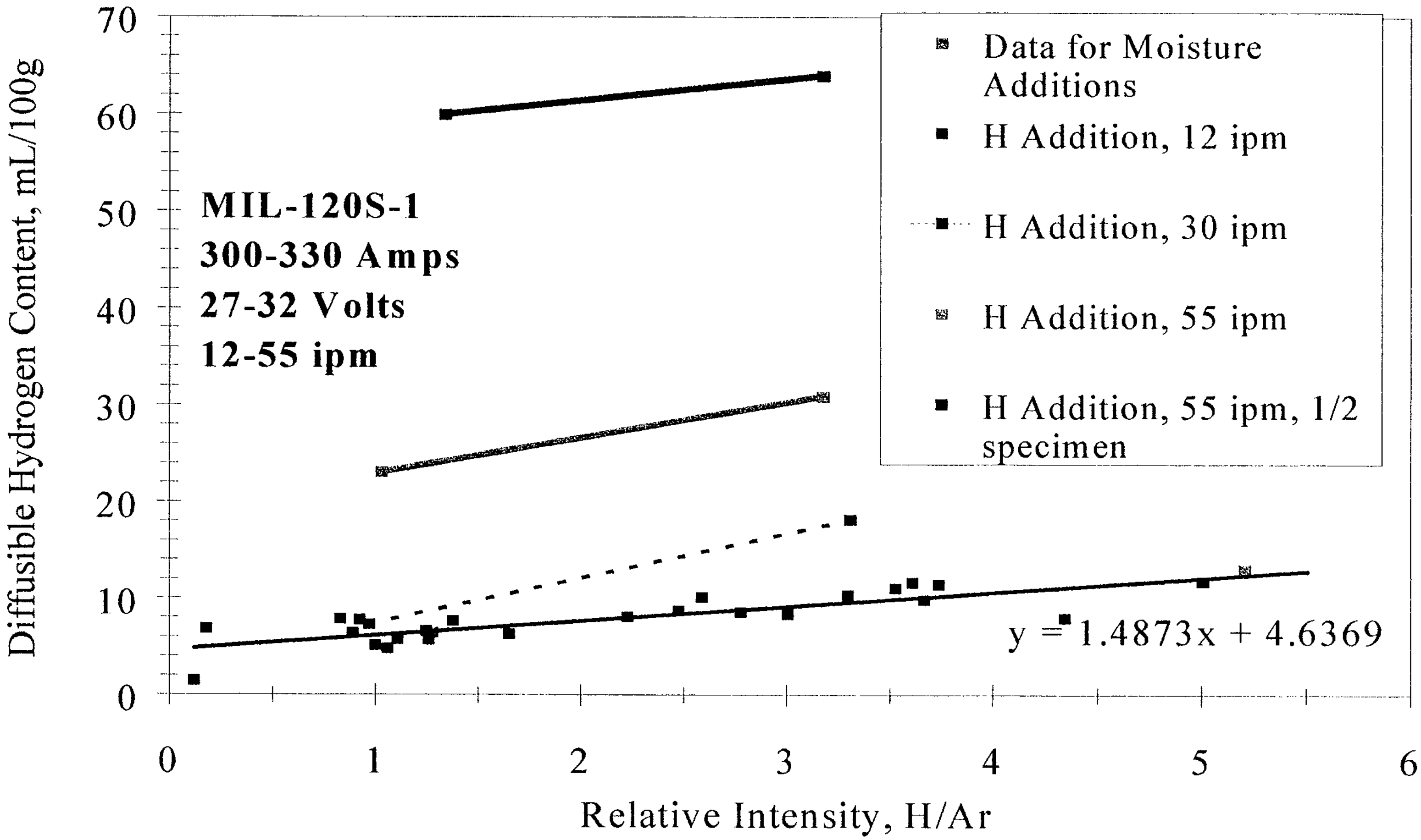
Task 2:	Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking
Activity 4:	Hydrogen Arc Sensing and Modeling to Predict Weld Metal Hydrogen Content
Organization:	USA-NSWCCD USA-Penn. State Univ.
Description:	The arc-sensing model will be extended to determine weld pool shape and time-temperature profiles associated with GMA welding. Currently, relationship between weld metal microstructures and toughness are being established. Hydrogen distribution and migration from the welding plasma to the solidified weld metal is being modeled. The model is being developed for GMA welding and will incorporate feed metal and resulting papilla characteristic of GMAW. The model utilized spectrographic data supplied by the hydrogen sensor to establish the initial species in the plasma.
Results:	Hydrogen emissions data was used to predict diffusible hydrogen test results using the Penn. State Univ. model. A cylindrical heat source has been developed for model development. The cylindrical heat source produced a papilla consistent with GMAW.
Plans:	The weld pool shapes and resulting thermal profiles will be validated. The effect of variations in welding parameters will be evaluated.
Status:	completed
Completion:	1998, Q4

Spectra Showing the Hydrogen and Argon Peaks With Hydrogen Added to Shielding Gas



Task 2, Activity 4, Hydrogen Arc Sensing to Predict weld Metal Hydrogen

Effect of Travel Speed, Moisture and Hydrogen Additions on Relative Intensity and Hd



Task 2, Activity 4, Hydrogen Arc Sensing to Predict weld Metal Hydroger

Task 2: Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity 5: Modeling of Hydrogen Cracking Behavior in a Repair Weld

Organization: Canada-DREA

Description: The time delay a structure is inspected for hydrogen cracking has important implications for production efficiency and cost effectiveness. This especially true in repair welding, where a quick turnaround is essential to maximize ship availability and minimize total repair costs. These same repair scenarios impose a fairly high risk of hydrogen cracking risk relative to new building. This being so it is important that a reasonable delay times be used prior to inspection for hydrogen cracking, when such inspections are deemed to be required.

What is proposed in this activity is that there be a sharing of perspectives, historical data, cracking times form test programs and modeling and other relevant information. This data would be combined in an interim operating assignment report to the Pannel and all countries concerned. This information would prove useful in the assessment of current practices, the documentation of the basis for current recommendations and the documentation of factors considered in developing practices for new steels used in Naval Construction (e.g. X-80, HSLA 65) and new welding practice and consumables.

Results: New Activity

Plans: NA

Status: in progress

Completion: 2001, Q3

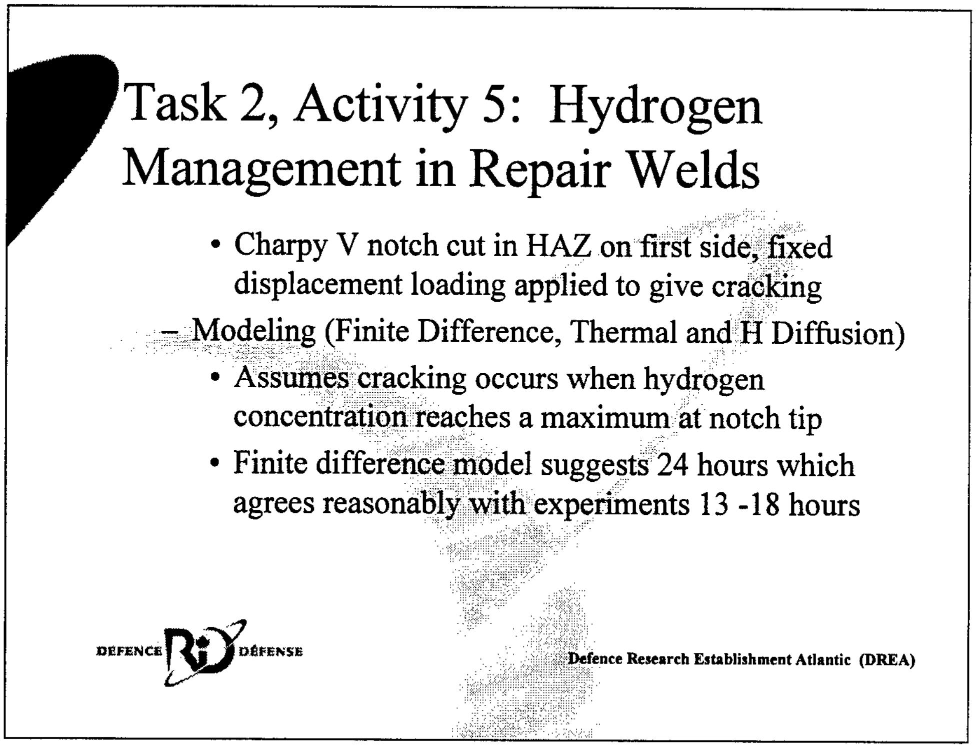
Task 2, Activity 5: Hydrogen Management in Repair Welds

- Questions to answer:
  - What is the required post weld delay time before inspection for hydrogen cracking ?
  - Can modeling be used to develop better welding process for hydrogen management?
- Approach: Experiments and Modeling
  - Experiments
    - 9mm A517 grade F plate, E110 -18 electrodes
    - 1 pass on one side of plate, 2 passes in U groove on other side with humidified rods

DEFENCE DÉFENSE Defence Research Establishment Atlantic (DREA)

The question of how long is it necessary to wait after welding for inspection for hydrogen cracking is being examined by modeling and experiments. Emphasis has been on repair welding in multipass weldments, a topic of current interest to the Canadian Navy. An initial series of experiments was done with 9mm A517 grade F plates and E110-18 electrodes. In these experiments, a Charpy V notch was placed in the weld heat affected zone of the weld and the other side of the weld was gouged out into a U-groove which was subsequently refilled with 2 passes made with humidified rods. The assembly was then loaded with fixed displacment loading and the time to cracking determined. Numerical modeling was done to estimate the temperature history and hydrogen redistribution by diffusion. To model the experimental weld, it was assumed cracking occurred when hydrogen concentration reached a maximum at the notch tip. The finite difference model suggested a 24 hour cracking time. This was in fairly good agreement with the experiments which showed a 13 to 18 hour cracking time. This work has been documented in a DREA contractor report [2] and a paper [3].

Follow on work to investigate delay times in repair welds in thicker HY 80 material will be completed by June 2001. This work will also address, to some degree, concerns raised in the previous study about the effect of variations in notch placement and welding parameters on results and the applicability of the model to longer delay times.

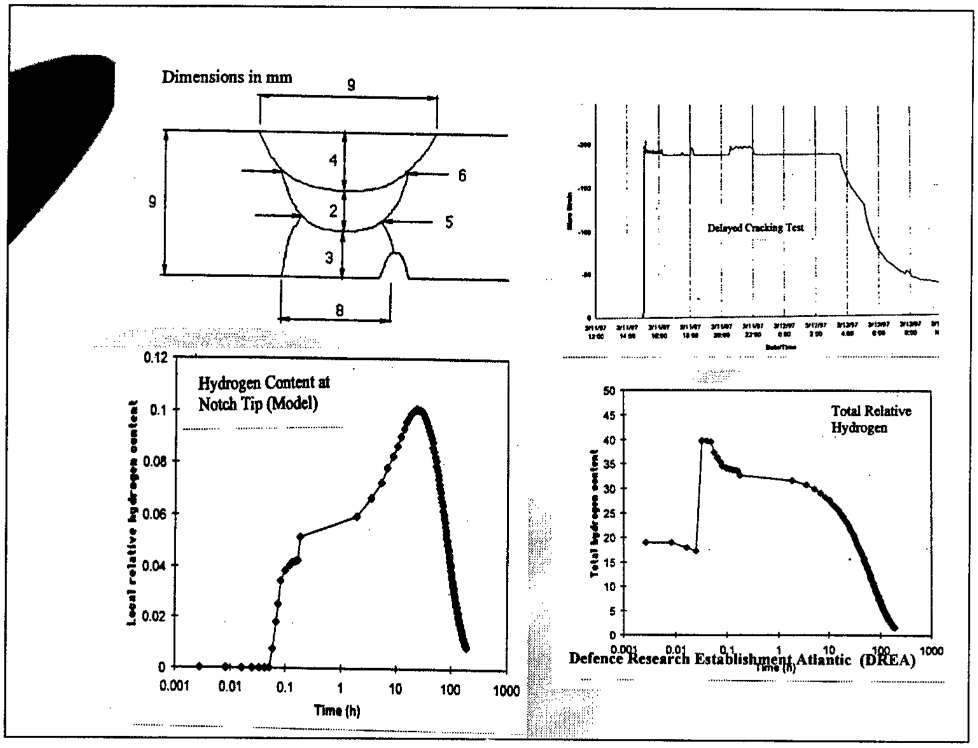


Reports

1. C.V. Hyatt and J.R. Matthews, *Delayed Hydrogen Cold Cracking in Ship and Submarine Weldments*, DREA TC 93/312, Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, 1993.

2. N. Pussegoda, B.A. Granville, and L. Malik, *Delayed Cracking in Naval Structural Steels,* DREA CR 97/420. Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, 1997.

3. B.A. Graville, L.N. Pussegoda, and L. Malik, *Prediction of Hydrogen Cracking in Multipass Welds in Low Carbon Steels*, in Abstracts and Summaries of the 2nd Canadian Forces/CRAD Meeting on Naval Applications of Materials Technology, edited by J.R. Matthews, Defence Research Establishment Atlantic, Dartmouth, Nova Scotia, pp. 632-645, 2-4 May, 1995,



The Figures above show:

Upper Left: The weldment dimensions used in the model and approximated in the experiments.

Lower Left: The hydrogen content at the notch tip as a function of time after welding, as predicted by the model. Assuming cracking occurs at peak hydrogen content, which is open to question, failure time is 24 hours

Upper Right: The output of a strain gauge on a constant deflection specimen. The drop after about 12.5 hours shows cracking has initiated. Specimens cracked between 12 and 18 hours.

Lower Right: Relative weldment total hydrogen. Comparing the two lower Figures highlights the importance of local concentration effects.

A final comment:

This technique offers great potential for the development and of welding procedures to avoid problems. For example, the time between passes in a multipass weld is an important variable which is seldom controlled.

Task 2: Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity 6: Eliminate Post Weld Heat Treatment by an Electrotransport Practice

Organization: USA-CSM

Description: The concept of using electrotransport to reduce diffusible hydrogen levels was evaluated using transport calculations.

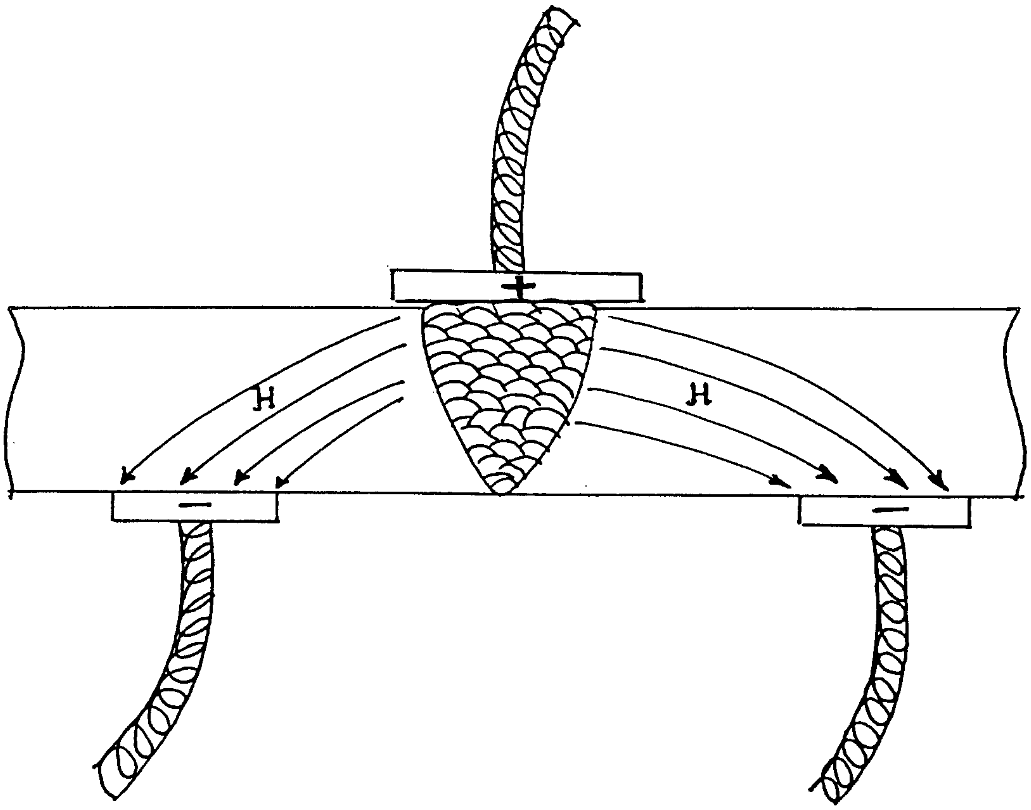
Results: The application of electrotransport during the welding thermal cycle may be useful in reducing hydrogen cracking susceptibility in small technical assemblies that might otherwise experience distortion or unacceptable microstructural changes as a result of conventional post weld heat treatment.

Due to the requirement of excessively high current, if electrotransport methods are to be applied to heavy section weldments, this technique initially appeared useful for only small weldments such as those found in precision assemblies. Discussions are in progress with the Center of Electromechanics of the Univ. of Texas to set an industrial demonstration project to illustrate that homopolar power sources can produce sufficient current and are portable enough to work in combination with the welding practice associated with heavy section weldments.

Plans: NA

Status: Completed

Completion: 1998, Q3


+
H
H
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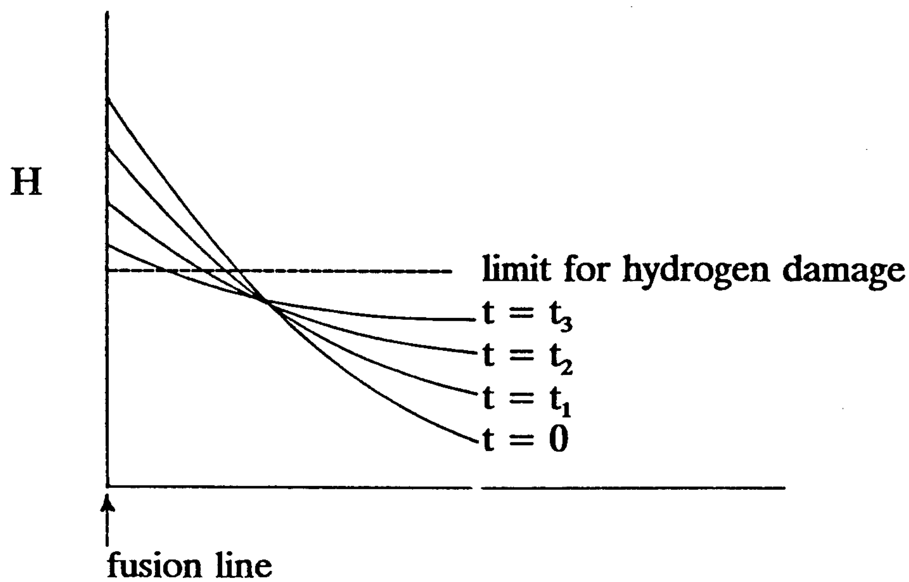
−


H
limit for hydrogen damage
t = t3
t = t2
t = t1
t = 0
fusion line

Task 2: Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity 7: Characterization of Undermatched Weldments

Organization: USA-NSWCCD
Australia-DSTO
Canada-DREA

Description: The use of undermatching weld metals may improve productivity of welding high strength steels by reduction or elimination of preheats.

Compared to cracking in the HAZ, the problem of weld metal HIC is still relatively new and less is known about its cause, however there are significant differences between weld metal and parent metal cracking. In particular, it has been found that weld metal cracking is known to occur at lower hardness values than HAZ cracking.

There is a minimum yield stress requirement of 690 MPa for weld metal in the QT steel plate used for the COLLINS Class submarines, however the actual yield stress values are often considerably higher. The yield stress values obtained in 188 procedure qualification tests were reviewed and histograms showing the distribution of yield stress values for all the qualified MMA procedures in COLLINS are given in the figure. This shows a classic normal distribution with a mean value of about 780 MPa. In other words, the actual weld deposit yield stress may be considerably greater than the minimum allowable. This increased yield stress gives limited benefit to the welded joint but is associated with a considerable increase in sensitivity to hydrogen cracking.

Work on this activity is directed at reducing the mean value of weld deposit yield stresses while ensuring that the welded joint is fit-for-purpose. To date the effort has focused on surveying literature in the area and making contact with other researchers in the area. The published evidence about reduced or undermatching weld deposit yield stress is conflicting with different tests or models producing significantly differing outcomes. Further work is required.

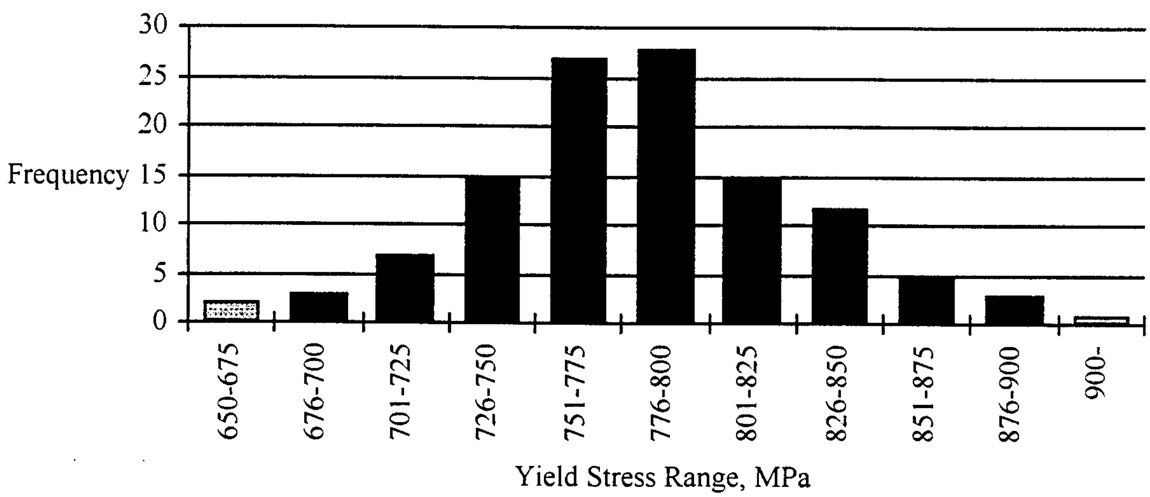
Results: NA

Plans: The scope and work statements will be defined and work will proceed.

Status: in progress

Completion: 2001, Q4

a) E12018-M2 Manual Metal Arc, All Welding Procedures



Distribution of yield stress values obtained during procedure qualification testing for all weld metals. Results with cross hatching are outside the acceptable range.

Task 2: Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking

Activity 8: Crack Mapping in a T-butt Joint

Organization: Australia-DSTO
USA-NSWCCD
Canada-DREA

Description: A T-butt joint was welded using conditions known to produce HIC. Three-dimensional plan of throughout the joint was prepared by milling down through the joint and inspecting at 2 mm intervals and recording the length and location of all cracking that was found. This work is being repeated for joints having butt and cruciform configurations.

Results: In one investigation, test plates were welded using procedures designed to deliberately generate cracking. The welding had been done with low preheat and interpass temperatures and the electrodes were damp at the time of welding. The plates were T-butt in configuration. When these plates were inspected at DSTO extensive sub-surface cracking was found. In fact, cracking was so extensive and cracks were so numerous that it was not possible to determine the number of cracks using ultrasonic techniques. Despite the large number of subsurface cracks, only one crack was found on the surface.

Serial "sections" through the joint were undertaken to map crack locations in the weld and HAZ. Multiple cracking was found along the root of the weld with cracks being equally spaced. On a few occasions isolated cracking was found, and these cracks were generally larger. A report on this investigation is completed. The reference is:

Ditchburn, R.J., Scala, C.M. and Dixon, B.F. (2000) '*Comparison of Techniques for nondestructive Inspection in Thick-section Welds of Pressure Vessel Steel*' Nineth International Conference on Pressure Vessel Technology. Sydney, Australia, 9-14 April.

In this work, the use of slits in the abutting member of a T-butt joint was not reliable means of generating cracks.

Plans: NA

Status: in progress

Completion: 2000, Q4

Comparison of techniques for nondestructive inspection in thick-section welds of pressure vessel steel

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1. ABSTRACT

This paper presents a comparison of defect detection and sizing results from two angle-beam ultrasonic investigations of a thick-section tee-butt welded joint containing transverse and longitudinal defects. The two ultrasonic techniques investigated were (i) automated P-scan and (ii) manual ultrasonics. The ultrasonic results for both were compared to a comprehensive magnetic particle inspection performed during subsequent sectioning of the joint.

2. INTRODUCTION

Many structures in military service, such as submarines, ships and armoured vehicles require thick section welds. To determine weld acceptability, the welds must be nondestructively inspected and the type, location and size of any defects determined. The challenge is to ensure reliable inspection but at the same time to minimise unnecessary inspection. While a range of nondestructive testing (NDT) techniques are possible candidates for thick weld inspection, the reliability of their application has been a topic of continuing concern. Even angle beam ultrasonics, which is the primary technique applied for inspection of thick-section welds, has been shown to have some limitations, in terms of defect detection and sizing, which require further investigation.

The tee-butt weld considered here forms part of a larger study being undertaken on a range of thick-section weld geometries to assess the capabilities of automated and manual ultrasonics to detect and measure the size of (i) transverse cracks and (ii) longitudinal defects,.

3. WELDED JOINT PREPARATION

The thick-section welded joint reported here is a 1000 mm long tee-butt joint with a 20 mm thick web and 35 mm thick flange. The joint was welded using high strength submarine steel plate (BIS 812 EMA) which is believed to have a low sensitivity to hydrogen cracking because it has a 'lean chemistry' (low in carbon equivalent). Artificial defects were introduced into the weld to replicate longitudinal fusion defects and cause transverse cracks to form at specific locations. The plates were also deliberately welded in a manner to encourage the formation of additional transverse cracks and numerous other weld defects, as described below.

The weld bevels were flame cut and ground, then three slits with depths of 3 mm, 4 mm and 6 mm were machined into the root, transverse to the weld direction. The slits were approximately 1 mm wide. Two 50 mm long shims, one 3 mm and the other 4 mm wide, were welded to the bevel faces using the GTAW process to replicate unfused side walls. Ceramic backing was used to control root penetration. The joints were welded with manual metal arc at normal preheat (120–180°C) for the first few passes. These joints were then filled with submerged arc using lower preheat, damp flux and water cooling between passes to induce transverse cracking. Capping was with submerged arc at normal preheat to reduce the risk of cracking in the weld cap.

The artificial defects were introduced only in the first third of the length of the joint, therefore only this portion of the joint is considered in this report. A photograph of the weld profile showing the vertical web welded to the horizontal flange is given in Figure 1. For the

purposes of the following analysis this weld profile is assumed to remain constant along the length of the weld. This is a reasonable assumption because the fill and capping passes were undertaken with automated submerged arc welding.

4. DEFECT EVALUATION

4.1 Ultrasonic Inspection Method

The tee-butt joint was ultrasonically inspected using two different techniques. The joint was firstly inspected using the automated P-Scan system using a Krautkrämer USK7-S flaw detector with a 2 MHz 60° angle beam probe, and at 4 MHz with probes at 0°, 45°, 60° and 70°. The inspection was carried out in accordance with TS-020 [1] because it represents an up to date military specification for critical thick-section weld applications. Secondly, the joint was inspected using manual ultrasonics in accordance with AS 2207 Level 1 [2]. The manual ultrasonics was performed using a Krautkrämer USK7-B flaw detector with a 4 MHz straight-beam probe (MB4S style), and with 4 MHz 45°, 60° and 70° angle beam probes (MWB style). For the manual ultrasonics, all defect indications were sized using the last significant echo technique as described in AS 2207.

It is of significance that the reference sensitivity under TS20 (used for the P-Scan inspection) is lower than that under AS 2207–1994 Level 1 (used for the manual ultrasonic inspection). AS 2207–1994 Level 1 specifies:

> – use the gain required to bring the signal from a 1.5 mm side-drilled hole which is at least 22 mm long, at the same beam path as the discontinuity, to 80% graticule height.

Whereas TS20 specifies:

> – use the gain required to bring the signal from a 3 mm side-drilled hole at least 22 mm long at the same beam path as the discontinuity, to 80% graticule height.

Under the evaluation conditions used in this paper all imperfection echoes equal to or greater than 20% graticule height of the amplitude from the side-drilled hole were evaluated for length and recorded.

4.2 Ultrasonic Inspection Results

Four discontinuities were detected using the automated P-Scan system (labelled A1–A4) while six discontinuities were detected using manual ultrasonics (labelled M1–M6). There were also numerous point reflectors detected along the entire length of the weld which greatly complicated the inspections. Most of these point reflectors were smaller than 2 mm in height and length. Due to the large number of these point reflectors their positions were not recorded.

Positions in the weld are defined using a right-handed *xyz* coordinate system with origin located on the weld centreline at the edge and on the top surface of the flange. The x coordinate gives the distance along the weld centreline, the y coordinate gives the perpendicular distance from the weld centreline, while the z coordinate gives distance into the flange (positive z) or distance above the flange (negative z). The ultrasonic data are shown graphically in Figure 2. The diagram on the left shows a *xy*-section of the tee-butt joint with all the indications given by automated P-Scan and manual ultrasonics overlayed. The diagrams on the right illustrate the weld profile in the *yz*-plane at the x position indicated and clearly show the height of the indications relative to the weld. The indication A2 was not adequately recorded and therefore could not be plotted fully.

4.3 Sectioning and Magnetic Particle Examination Results

To assess the validity of the two ultrasonic techniques and allow their comparison, the joint was progressively sectioned to uncover the discontinuities contained in the joint. Sections were taken parallel to the *xy*-plane. The sectioning commenced in the web and proceeded into the flange at intervals of $\Delta z \approx 0.5$ mm. Following each cut a magnetic particle inspection was conducted to highlight the defects present and the location and size of the discontinuities were

recorded. These results are tabulated in Table 1 along with the labels of the corresponding indications given by the ultrasonic inspections. Given that the depth of each cut was ≈ 0.5 mm there is an uncertainty of ≈ 0.5 mm in the z direction measurements and the possibility that defects smaller than 0.5 mm in this direction be missed entirely by magnetic particle inspection.

Due to the great number of small transverse cracks that were present, these cracks were not recorded individually but were grouped together as bands of transverse cracks to simplify the recording procedure. These numerous transverse fine cracks were typically less that 2 mm in length, although a small number were up to 4 mm in length. This fine cracking data is not tabulated in Table 1.

The diagrams in Figure 3 show a comparison of the combined ultrasonic data with the magnetic particle data for two different sections parallel to the *xy*-plane. For both sections in Figure 3, two diagrams are shown, the upper diagram shows the magnetic particle data from Table 1 including the locations of the numerous fine cracks (typically less than 2 mm in length) detected by magnetic particle inspection which were plotted as bands of transverse cracks. The lower diagram of each section shows the combined automated and manual ultrasonic data. The shaded region shows the weld metal.

5. RESULTS AND DISCUSSION

5.1 Automated Ultrasonics and Manual Ultrasonics vs Magnetic Particle Inspection

Comparison of the ultrasonic inspection with the magnetic particle inspection results shows that every indication given by the ultrasonic inspections was verified by the magnetic particle inspection, and every significant magnetic particle indication was also verified by either one or both of the ultrasonic techniques.

It is evident from Figure 2 that three indications given by automated ultrasonics corresponded well with indications given by manual ultrasonics, ie A1 corresponded to M2/M3, A2 to M4, and A4 to M5. Three other indications were detected by one ultrasonic technique only and not verified by the other, ie A3 (longitudinal) was given by automated ultrasonics only, while M1 (longitudinal) and M6 (transverse) were given by manual ultrasonics only. The failure of the automated ultrasonics to detect M1 was not surprising given that this system setup was unable to inspect for defects within approximately 25 mm of the end of a specimen. However, concern exists as to why the automated ultrasonics failed to detect the large transverse defect M6 in our investigation. The manual ultrasonics failed to detect the longitudinal defect A3 but this defect was small and therefore its non-detection was of a lesser concern than the non-detection of a large transverse defect.

In general, the size of the defects was not well predicted by ultrasonics. Both indications A4 and M5 had an error of 28 mm for their length in the x direction. In most other cases the error ranged from 3 to 7 mm in at least one direction for each defect.

Not only is the detection and correct sizing of defects important, but also the accurate determination of the defect's location. Inspection of the results showed that most end positions given by ultrasonics were within 5 mm of those given by the magnetic particle inspection. Of the defects with errors in end position greater than 5 mm, only four end positions had an error of greater than 10 mm. Despite these errors in the end positions, all the ultrasonic indications either overlapped or were within 7 mm of the corresponding indication given by the magnetic particle inspection. From a practical point of view, therefore, the defects giving ultrasonic indications would all have easily been found during gouging before a weld repair.

It appears that the ultrasonic inspections have generally predicted the defects below their actual locations, ie, a more positive z value. The ultrasonic indications A2, M3, M4 and M6

all coincided, to some extent, with indications given by magnetic particle inspection. All the other ultrasonic indications were lower (a more positive z value) than those detected by the magnetic particle investigation and therefore do not appear on the same xy-section diagram (Figure 3). Furthermore, the transverse indication M6, is the only ultrasonic indication that extended above (a more negative z value) its corresponding indication given by magnetic particle inspection.

5.2 Effectiveness of Artificially Introduced Defects in Weld Preparation

The slits that were machined into weld preparation bevels successfully caused transverse cracks and the shims that were welded on the bevels successfully caused longitudinal discontinuities at the desired locations. All the artificially introduced defects except the smallest slit (I1) were subsequently verified by the ultrasonic and magnetic particle inspections. I1 was only 3 mm in depth and may have been melted out during welding. In addition to the artificially introduced defects two other large defects were detected by the ultrasonic or magnetic particle inspections, namely M1 and A3.

The other methods used to encourage the formation of transverse cracks, ie exposure of the flux to air and cooling of some weld passes with water, resulted in a large number of small transverse cracks. This reflects the situation in practice where it is commonly found that transverse cracking occurs either as an isolated large crack or a series of small cracks along the weld. The cracks were identified by the ultrasonic operator and were reported.

It was thought that the presence of the numerous fine transverse cracks might mask other significant defects by scattering the ultrasonic beam and prevent the defects from being detected. In this study this does not appear to be the case. However, because of the scattering from the fine cracks, during the manual ultrasonic inspection, extremely careful probe manipulation and concentration were required by a highly skilled inspector. This level of concentration and skill may not always be achieved in a production environment and the chance of missing defects will increase.

5.3 Observations on the Locations and Extent of Transverse Cracking

The welding parameters chosen for this work caused a significant number of transverse cracks through the entire length of the weld. Since the locations of these cracks were not recorded for either ultrasonic technique, a comparison cannot be made with those indications detected by the magnetic particle inspection. However, it is instructive to examine the locations of both small and large transverse cracks relative to the weld as determined by magnetic particle inspection.

As illustrated in Figure 3 a significant number of fine transverse cracks occurred in parent metal high up the web. There were fewer fine transverse cracks at lower sections in the web once the weld metal spanned the full thickness of the joint. The greatest number of fine transverse cracks occurred in the flange (ie, positive z values). In this region the cracks were mostly confined to the flange weld metal. However, a number (Figure 3, $z = +1.8$ mm) were in parent metal. This area about the root of the weld was undertaken with low preheat welding conditions and it was anticipated that cracking would occur in this region. However, the fact that hydrogen cracking extended well into the parent metal was not anticipated, since this parent metal is supposed to be highly resistant to cracking.

Both of the large transverse defects (M6 and A2/M4) began high up in the web and then extended well into the flange (Figure 2 and Figure 3). In particular, the large transverse defect M4 finished well into the flange parent plate, 6 mm below the weld metal. This defect also broke the surface on both sides of the web, traversing the web parent metal.

In practice, most transverse cracking is sub-surface and it is most unusual for the cracking to be this large and to break the surface. Even in the current situation, where low heat input

welding procedures were used for some of the fill passes, it was not expected that cracking would travel into regions of weld where qualified welding techniques were used, or into 6 mm of parent metal. This demonstrates that significant cracking can occur in both welds and parent metal of this steel when inappropriate procedures are used.

The fact that both large and small transverse cracks were found in parent metal clearly indicated that this steel is susceptible to transverse hydrogen cracking, despite its lean chemistry and quite high level of weldability. However, the evidence suggests that parent metal cracking initiated in weld metal and grew into the parent metal.

It was also observed (Figure 3) that the fine transverse cracks were absent near where large transverse cracks occurred (see in particular, M4) indicating that the larger cracks formed first and thereby dissipated the residual stress at these locations. Work is currently under way to estimate the level of stress at the first small cracks away from the larger cracks, since this provides an indication of the level of residual stress necessary for crack formation when using these welding conditions and materials.

6. CONCLUSIONS

A comparison of manual and automated P-Scan ultrasonic testing of a tee-butt joint with magnetic particle inspections of slices through the same joint has shown that all significant ultrasonic indications given were verified by the magnetic particle inspection, and that every magnetic particle indication was verified by either one or both of the ultrasonic techniques. However, the ultrasonic inspections have generally predicted the defects lower (closer to the flange) than their actual locations as determined by magnetic particle inspection. Furthermore, concern exists as to why (i) the automated ultrasonics failed to detect the large transverse defect M6 (length = 18 mm, height = 13.4 mm), and (ii) the manual ultrasonics failed to detect the small longitudinal defect A3 (length = 5 mm, height = 0.5 mm). Concern also exists about the inaccuracies in sizing defects by both manual and automated ultrasonic techniques. Further measurements on additional specimens are required to resolve this problem.

The welding procedure and the introduction of artificial defects were successful in producing transverse and longitudinal cracks at the desired locations. However, large numbers of transverse cracks were generated throughout the entire length of the weld. This complicated the ultrasonic and magnetic particle inspections for larger defects because the smaller defects generated a significant 'noise'.

The location of the transverse cracking was significant. Both the large and fine transverse crack formations occurred in the parent metal as well as the weld metal, thereby proving that the parent metal is not immune to cracking, despite its 'lean' chemistry. Furthermore, the fine transverse cracks were absent near where large transverse cracks occurred, indicating that the larger cracks formed first and relieved the tensile residual stresses at these locations.

ACKNOWLEDGEMENTS

The authors wish to thank the assistance of Mr Joe Donato, Mr Paul Calleja and Mr Ian Jackson during the sectioning and magnetic particle inspection of the joint. The plotting of data by Mr Joe Donato is also gratefully acknowledged.

REFERENCES

[1] Technical Specification TS-020, Revision 11, Quality control regulations, inspection and examination of welds and rules for evaluation and approval. Kockums Submarine Systems AB, 1995.

[2] Australian Standard. AS 2207–1994, Non-destructive testing–Ultrasonic testing of fusion welded joints in carbon and low alloy steel, Standards Association of Australia, 3rd edition, 1994.

Table 1: Tabulated data showing the locations of the magnetic particle indications. For each indication the label for the corresponding indication given by the ultrasonic inspections is also given.

Magnetic Particle Inspection				
x	**y**	**z**	**Indication Type**	**Corresponding Ultrasonic Indication Label**
0 to 29	–3	–10.7 to –9.8	Longitudinal	M1
137 to 138	-8 to 14	-10.3 to 3.3	Transverse	End of A1, M2, M3
88 to 138	–4	–9.3 to –6.2	Longitudinal	A1, M2, M3
188 to 193	–18 to 19	–21.9 to 9.7	Transverse	A2, M4
228 to 233	0	–2.6 to –2.1	Longitudinal	A3
261 to 329	–7 to –4	–10.3 to –9.3	Longitudinal	A4, M5
330 to 333	0 to 18	–8.8 to 4.6	Transverse	M6

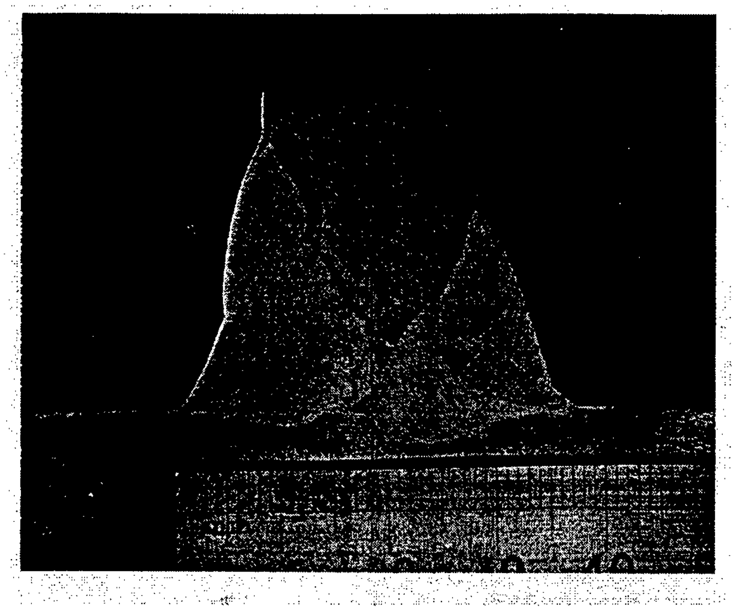


Figure 1: The weld profile in the yz-plane at $x = 0$ mm showing the vertical web welded to the horizontal flange. Each division on the ruler is 1 mm. Etchant was aqueous nitric acid.

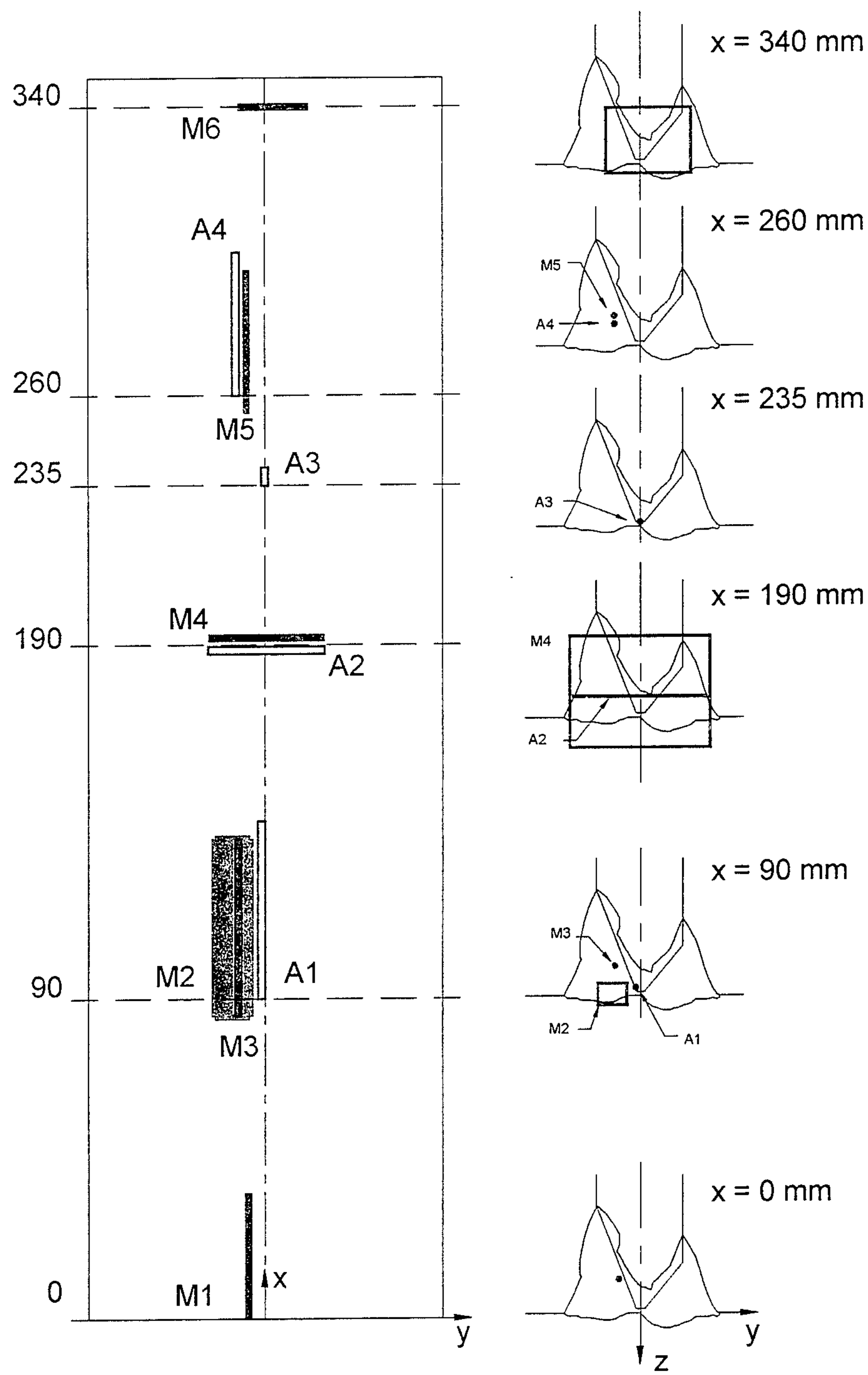


Figure 2: The diagram on the left shows xy-section of the tee-butt joint with all the indications given by automated P-Scan (A) and manual ultrasonics (M) overlayed. The diagrams on the right show a yz-section of the joint at the x position indicated.

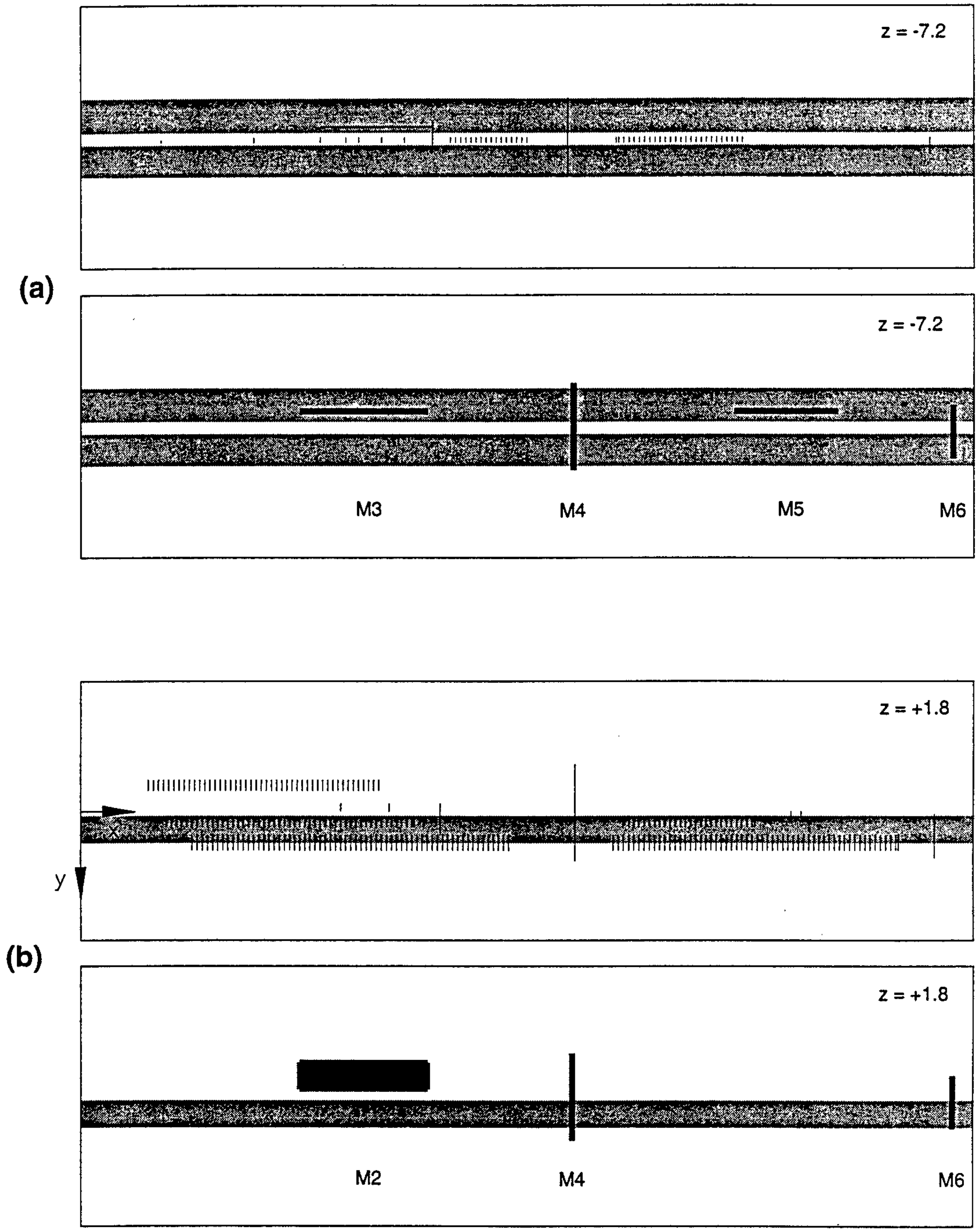


Figure 3: Diagrams of xy-sections of the joint showing a comparison of the ultrasonic and magnetic particle data at the two different sections (a) z = –7.2 mm and (b) z = 1.8 mm. For each section the upper diagram shows the magnetic particle data while the lower diagram shows the combined ultrasonic data.

Task 2:	Determination of the Relationship between Welding Parameters (Including Hydrogen Content) on Multiple Pass Weld Transverse Cracking
Activity 9:	Hydrogen Content in Multipass Welds
Organization:	UK-DERA Canada-DREA USA-NSWCCD Australia-DSTO
Description:	Determination of the influence of multiple thermal experiences due to multipass welding on the resulting hydrogen content.
Results:	NA
Plans:	Searching for collaboration.
Status:	in progress
Completion:	2002, Q4

4.3 TASK 3

Development of High Strength Steel Filler Metals to be used without Preheat

TASK 3

DEVELOP HIGH STRENGTH STEEL FILLER METALS TO BE USED WITHOUT PREHEAT

1. Preheat Free MMA and FCA Welding Consumables
   Australia-DSTO
   Australia-CISRO-DMT
   USA-NSWCCD
   Canada-DREA

2. Development of ULCB Wires
   USA-NSWCCD
   Australia-DSTO
   Canada-DREA

3. ULCB Wire Evaluation
   USA-NSWCCD
   Australia-DSTO

4. Evaluation of ULCB MCAW Consumables
   USA-NSWCCD

5. Fluoride Additions to Control Weld Hydrogen Content
   USA-CSM

6. Austenite Decomposition Temperature as Hydrogen Cracking Indicator
   USA-CSM
   USA-NSWCCD

7. Multiple Pass Weld Metal Properties Cooperative Project
   Australia-CISRO
   USA-CSM

8. Reduction of Diffusible Hydrogen Through The Use of Weld Metal Traps
   USA-CSM
   USA-Lincoln Electric

9. Analytical Methods to Evaluate Weld Hydrogen Content and Hydrogen Distribution
   USA-CSM
   USA-SUNY Albany
   USA-Lincoln Electric

TASK 3 (page 2)

10. Understanding the Influence of Alloy Additions on Microstructure and Mechanical Properties of Weld Metal from Gas-Shielded Processes
    - Australia-CISRO-DMT
    - USA-CSM
    - UK-DERA

11. Evaluation of the Influence of Retained Austenite on Hydrogen Assisted Cracking
    - UK-Cockrane
    - USA-NSWCCD
    - Australia-DSTO
    - Canada-DREA
    - USA-CSM

Task 3 Develop High Strength Steel Filler Metals to be used without Preheat.

Activity	Status	Results	Description	Organization
1. Preheat free MMA and FCA Welding Consumables	in progress	Excessive oxygen levels in experimental Ni-Mn-Mo weld metals have resulted in unsatisfactory toughness.	Satisfactory tensile results were obtained for experimental Ni-Mo-Mn, low C, FCA and MMA consumables. Charpy results were variable. For FCA Charpy results were satisfactory/ marginal with O slightly high at 0.04 wt%. For MMA weld metals, Charpy results were unsatisfactory with a high O level of 0.06 wt%. New iteration is focussing on higher Mn and lower O. New MMA chemistry has C ultralow at 0.01 wt%.	Aust. – DSTO Aust. – CISRO-DMT USA – NSWCCD Canada - DREA
2. Development of ULCB Wires (80-130 ksi yield strength)	completed	Development of ULCB wires has been completed and thorough evaluation of mechanical properties is in progress.	Statistical evaluation of resulting data identified as factors controlling mechanical properties. Regression equations describing the composition, cooling rate, transformation temp., and grain size on YS, UTS, and CVN energy at -60°F have been finalized.	USA – NSWCCD Aust. – DSTO Canada - DREA
3. ULCB Wire Evaluation (80 ksi yield strength)	in progress	Eval. of final matrix of 4 experim. wires, Alloys 1-4, was successfully completed. Prototype production heat is in production.	Mechanical property and weldability evaluation of 4 experimental wires is complete. All wires met mechanical property requirements. 3 of 4 wires met weldability goals. Explosion crack starter testing was successfully completed. A prototype production heat based on Alloy 2 is in production.	USA - NSWCCD
4. Evaluation of ULCB MCAW consumables	in progress	Continuation of ULCB wire investigation	This task will evaluate 4 MCAW wires produced to meet weld deposit chemistries specified by NSWCCD	USA - NSWCCD Aust. - DSTO

Task 3 (continued) Develop High Strength Steel Filler Metals to be used without Preheat.

Activity	Status	Results	Description	Organization
5. Fluoride additions to control weld hydrogen content	in progress	Theo. & experimental evidence has demonstrated the use of fluoride addition and can achieve low diffusible H contents.	Use of fluoride and optimal amounts of oxygen introduced to the welding plasma to control weld hydrogen content is being evaluated.	USA - CSM
6. Austenite decomposition temperatures as hydrogen cracking indicator	completed	Preliminary results suggest value of using M_S temperatures	M_S temperatures were shown to delineate cracking tendencies of high strength steels in hydrogen environment. The difference in MS temperatures of base metal and weld metal can indicate whether cracking will occur in the weld or HAZ. The successful application of MS temperatures as a cracking induces results from the large differences in hydrogen solubility and diffusion coeff. Between ferrite (martensite) and austenite.	USA - CSM USA - NSWCCD
7. Multiple pass weld metal properties cooperative project	in progress	Studies to date have included assessments of the influence of Mn, Si, Ti, Al, and B on properties of welds from these wires.	A cooperative research project between CSIRO and CSM is in progress to better understand the influence of alloying additives on the microstructural and mechanical properties of weld metal for shielded arc welding processes. The work is proceeding at each institution and visitations have been made to share data, to discuss alloying and thermal processing models, and to design needed experiments.	Aust - CSIRO USA - CSM
8. Reduction of diffusible hydrogen through the use weld metal traps	in progress	Yttrium ferroadditions can make significant reductions in diffusible hydrogen	The use of weld metal hydrogen traps to reduce the available diffusible hydrogen content is being investigated.	USA - CSM USA – Lincoln Elect.

Task 3 (continued) Develop High Strength steel Filler Metals to be used without Preheat.

Activity	Status	Results	Description	Organization
9. Analytical methods to evaluate weld hydrogen content and hydrogen distribution	in progress	Methods to measure weld hydrogen distribution are being evaluated. A stick-on tape with an electronic sensor for measuring diffusible hydrogen appears possible.	A number of methods have been used to demonstrate that the weld hydrogen content is not uniform in its distribution but has localized high contents which should be of major concern to the integrity of high strength steel welds. These localized hydrogen contents are most likely the cause in the spread of the measured hydrogen cracking results in welds that have acceptably low measured diffusible hydrogen contents.	USA - CSM USA – SUNY Albany USA – Lincoln Elec.
10. Influence of alloy additions on microstructure and mech. prop. of weld metal from gas-shield processes	completed	Literature review has been published. Consumable with B have been made and is being investigated on its influence on microstructure.	This project is a strategic study in which the influence of well controlled additions of alloying and microalloying elements to experimental gas-shielded cored welding wires will be investigated. Major aspects of the project include manufacutre of cored consumables from high purity materials and assessment of details of the welds form these consumables with regard to mechanical properties, micrstructure development and influence of non-metallic inclusions.	Aust.-CISRO-DMT USA-CSM UK – DERA
11. Evaluation of the influence of retained austenite on HAC	initiated	Preliminary research has been performed. Results reported in Trends in Welding Research '98.	Retained austenite in high strength steel weld is a significant high temperature bulk hydrogen trap. Retained austenite may transform to martensite with changes in service temperature and plastic strain, which can cause hydrogen release and resulting in hydrogen cracking. The existence of retained austenite means low reported diffusible hydrogen values when using existing testing methodologies.	USA-CSM USA-NSWCCD Aust. – DSTO UK – Cockrane Canada - DREA

Task 3: Development of High Strength Steel Filler Metals

Activity 1: Preheat Free MMA and Flux Cored Arc Welding Consumables

Organization: Australia-DSTO Australia-CISRO-DMT
USA-NSWCCD Canada-DREA

Description: The review of the status of preheat free consumables is continuing. Experimental MMA and FCA consumables, each at two different composition levels have been received from DMT/CSRRO, Adelaide.

Results: "Preheat free" formulations for both manual metal arc and flux-cored arc consumables prepared by DTSO have been trialed. All consumables delivered acceptable welding characteristics with a stable arc, easy slag removal and satisfactory bead appearance. Most of the experimental weld metals met our minimum YS of 690 MPa. In general, Charpy toughness was quite poor and did not meet our objective of 64J @ -51C. Subsequent metallographic examination showed that unexpectedly high proportions of unrefined primary microstructure of between 40-50% may have contributed to this poor result. This compares to 20-25% which has been observed during the actual welding of the COLLINS submarine.

In the most recent experiments the toughness of MMA preheat free consumables deposited in both the down-hand and vertical-up positions has been compared. The results are set out below.

Pass Value	Down Hand	Vertical Up
Charpy Toughness		
75 J @ -18 C	45 J, 24 J	33 J, 38 J
47 J @ -51 C	19 J, 35 J	22 J, 30 J
0.2% proof stress		
690 MPa	686 MPa, 689 MPa	761 MPa, 792 MPa

It can be seen that poor Charpy toughness was encountered in both cases. High proportions of unrefined primary structure were again encountered. Significant differences in oxygen content were noted, with 0.067 wt.%, being measured for the vertical-up weld compared to 0.039 wt.% for the downhand weld.

Plans: Future plans include investigating the role of welder skill, the proportion of unrefined primary structure and oxygen content of the strength and toughness of low C, MMA consumables. Metallographic studes of the weld metal microstructure are planned as are further discussions with NSWCCD on consumable formulations. Tests to assess the resistance to weld metal hydrogen cracking are also planned.

Status: in progress

Completion: 1999, Q4

‘PREHEAT FREE’ CONSUMABLES - PROGRESS

- 7 MMA and 3 FCA consumables investigated to date.
- Welds deposited in downhand position.
- 0.2% proof strength objective - 690 MPa for BIS 812 EMA steel.
- All consumables of the ultra low C-Ni-Mn-Mo type.
- Core wire for MMA is 0.01%C.
- Weld metal oxygen levels of 0.035% - 0.045% now being achieved.
- Acceptable welding characteristics for both MMA and FCA.
- 690 MPa objective generally exceeded - except M3 and F1.
- Charpy toughness results generally disappointing - except M3.
- These welds generally had a high proportion of primary solidification structure, 60% compared to the expected 30%.

Weld Metal Chemical Analyses

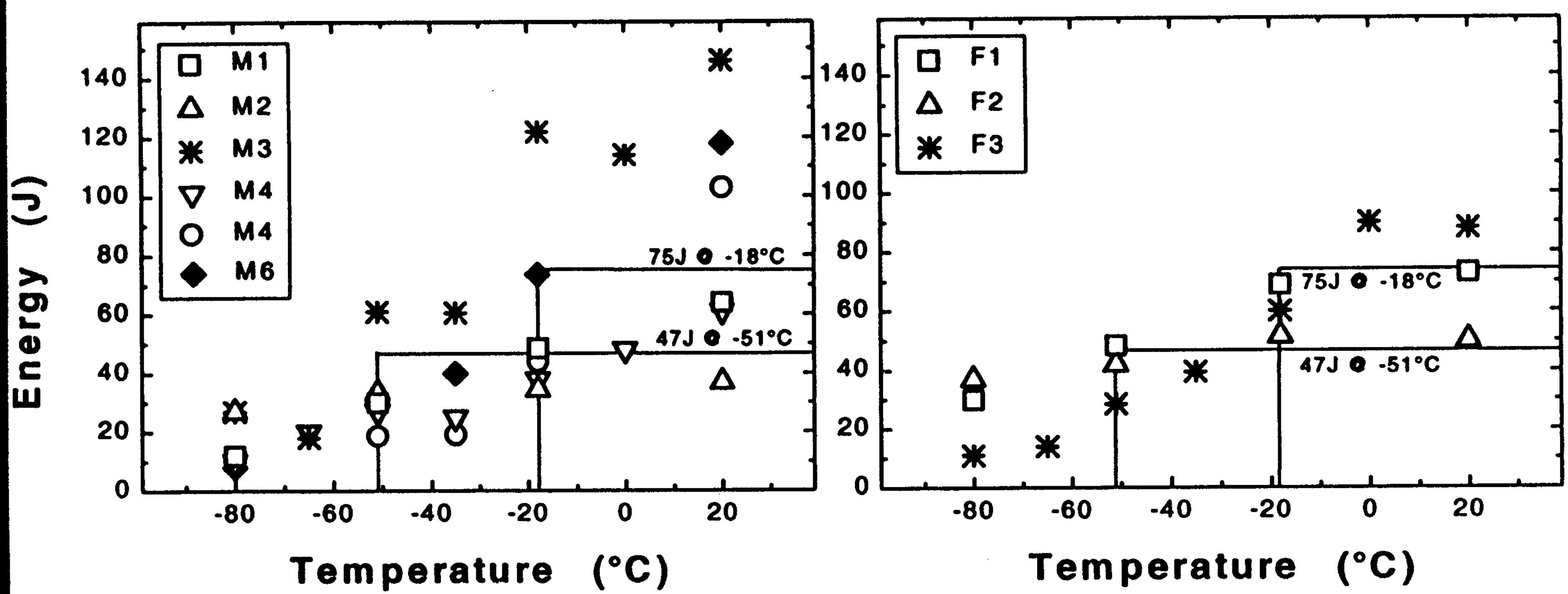
	C	Mn	Si	S	P	Ni	Cr	Mo	Cu	V	Nb	Ti	Al	O	N
M1	.03	1.07	.09	.012	.013	2.84	.02	.46	.03	.01	<.01	<.01	<.005	.066	.014
M2	.03	.67	.11	.012	.013	5.23	.26	.65	.05	.01	<.01	<.01	.005	.057	.012
M3	.02	1.67	.27	.013	.016	2.02	.03	.16	.03	.01	<.01	<.01	<.005	.044	.0078
M4	.02	2.60	.61	.012	.016	2.05	.04	.17	.03	.01	<.01	.01	<.005	.037	.0091
M5	.02	2.30	.53	.011	.016	1.95	.05	.21	.02	.011	.001	.005	<005	.037	.011
M6	.02	1.91	.38	.011	.018	1.95	.03	.20	.02	<.01	<.01	<.01	<.005	.037	.013
F1	.04	1.55	.16	.010	.017	2.78	.02	.52	.03	.01	<.01	<.01	.005	.044	.0043
F2	.03	1.10	.21	.010	.017	5.40	.28	.74	.05	.01	<.01	.01	.006	.044	.0028
F3	.03	2.19	.57	.013	.014	2.40	.02	.23	.04	.01	<.01	.02	.013	.044	.0035

M = MMAW F = FCAW

'PREHEAT FREE' CONSUMABLES - Welding Conditions

- **Coupon: 35mm thick BIS 812 EMA steel, 10mm root gap, 45° single vee.**
- **Downhand position.**
- **2.0 kJ/mm heat input.**
- **No preheat, maximum interpass temperature 50°C.**
- **MMAW: electrodes dried at 350°C for 1 hour then held at 100°C. electrode diameter: 3.25mm.**
- **FCAW: 1.2mm dia. Wire, Ar/5%CO_2 @ 15 l/min, reverse polarity, typical 300 A, 26V, 4mm/sec.**

Preheat-free Consumables



MMAW

FCAW

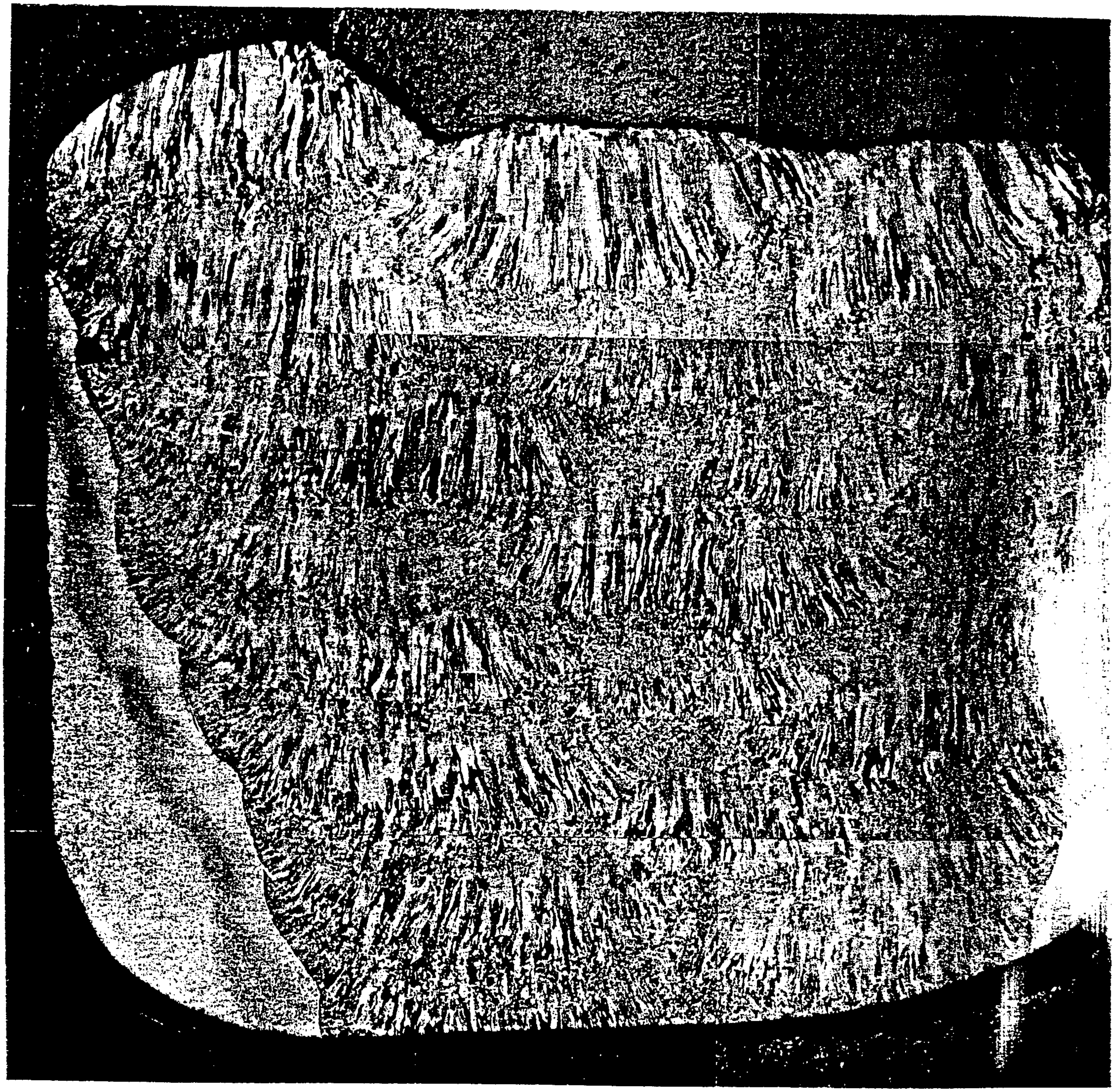
Tensile Test Results

	0.2% PS (MPa)	UTS (MPa)	El (%)	R of A (%)
M1	(a)	(a)	(a)	(a)
M2	784	831	18	41
M3	613	665	21	67
M4	791	815	16	42
M5	738	780	29	66
M6	753	786	28	66
F1	678	734	24	66
F2	715	(b)	(b)	(b)
F3	757	795	15	44

M = MMAW F = FCAW Average of two tensile tests

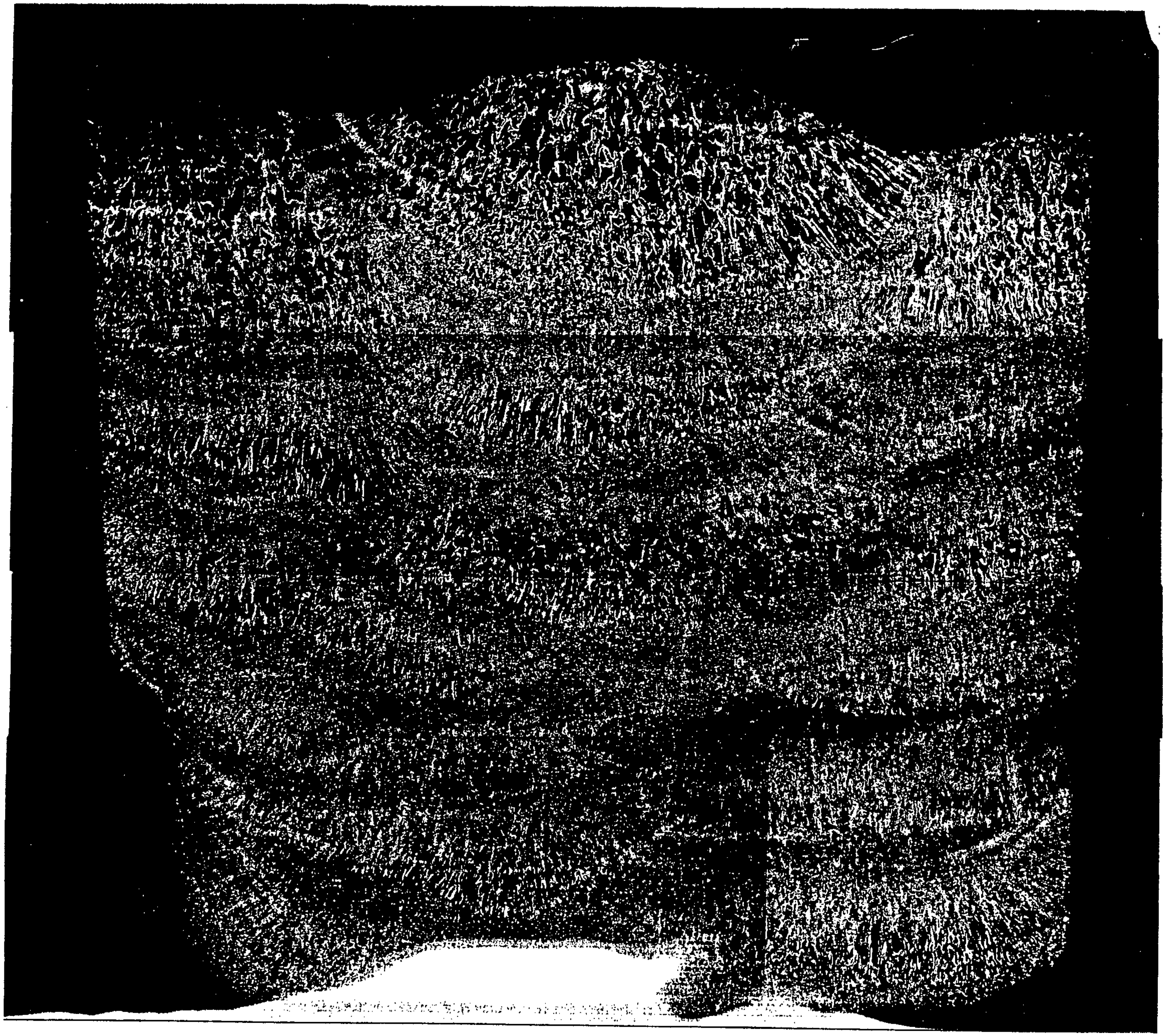
(a):Failed at slag inclusions (b):Failed at lack of fusion defects

Microsample



x37.5

Microsample



'PREHEAT FREE' CONSUMABLES - FUTURE WORK

- **More experimental compositions. Further discussions with NSWC.**
- **Evaluation of weld metal non-metallic inclusion distribution.**
- **Downhand vs vertical-up welding - determine effect of primary solidification microstructure.**
- **Microstructure evaluation.**
- **Evaluation of hydrogen induced cracking susceptibility using the Davidson *Controlled Cracking Test.***

Task 3: Development of High Strength Steel Filler Metals

Activity 2: Development of Ultra Low Carbon Wires

Organization: USA-NSWCCD
Australia-DSTO
Canada-DREA

Description: Development of Ultra Low Carbon Bainite (ULCB) wires (80-130 ksi yield strength). Chemical analyses, microstructural evaluation, transformation studies, and mechanical property assessments were performed on several ULCB welds. Statistical evaluation of resulting data identified composition, cooling rate, transformation temperature, and grain size as factors controlling mechanical properties. Regression equations describing these relationships are being developed and refined.

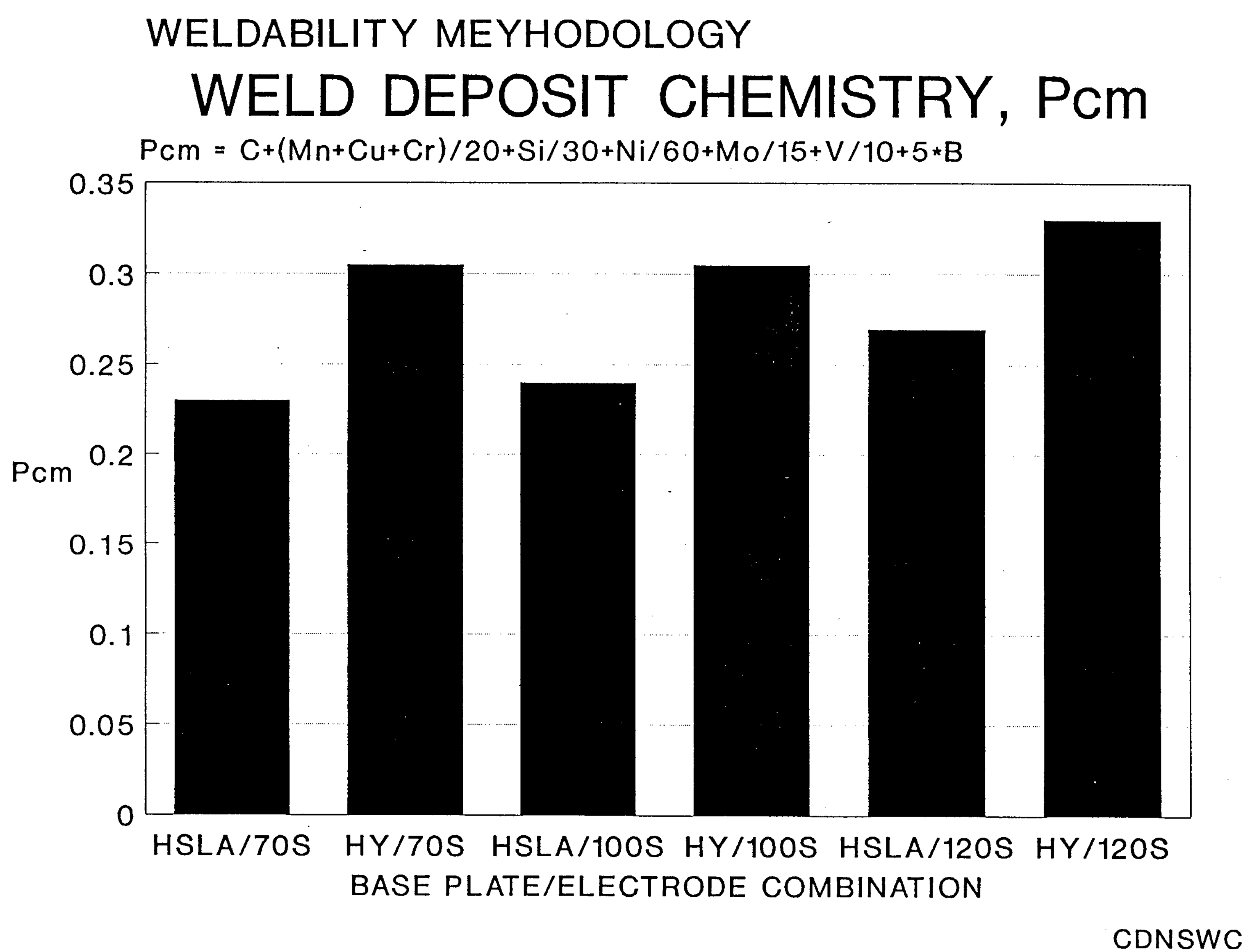
Results: The Development of ULCB wires (80-130 ksi yield strength) has been completed and thorough evaluation of mechanical properties and weldability is in progress at NSWCCD. The wire will soon be available for round robin evaluation. DSTO is now in position to participate in round robin testing using 690 Mpa yield QT microalloy steel. NSWCCD could conceivably start the round robin testing in December.

Welds have been fabricated with various shielding gases and welding thermal cycles to produce weld metal of various oxygen and nitrogen contents and grain sizes. The results of this anlysis were incorporated into the above equations. This work was presented at the International Conference on Advances in Welding Technology November 6-8, 1996 and the PRICM 3 conference on July 15, 1998. A copy of these papers will be forwarded with the final TTCP report.

Plans: NA

Status: completed

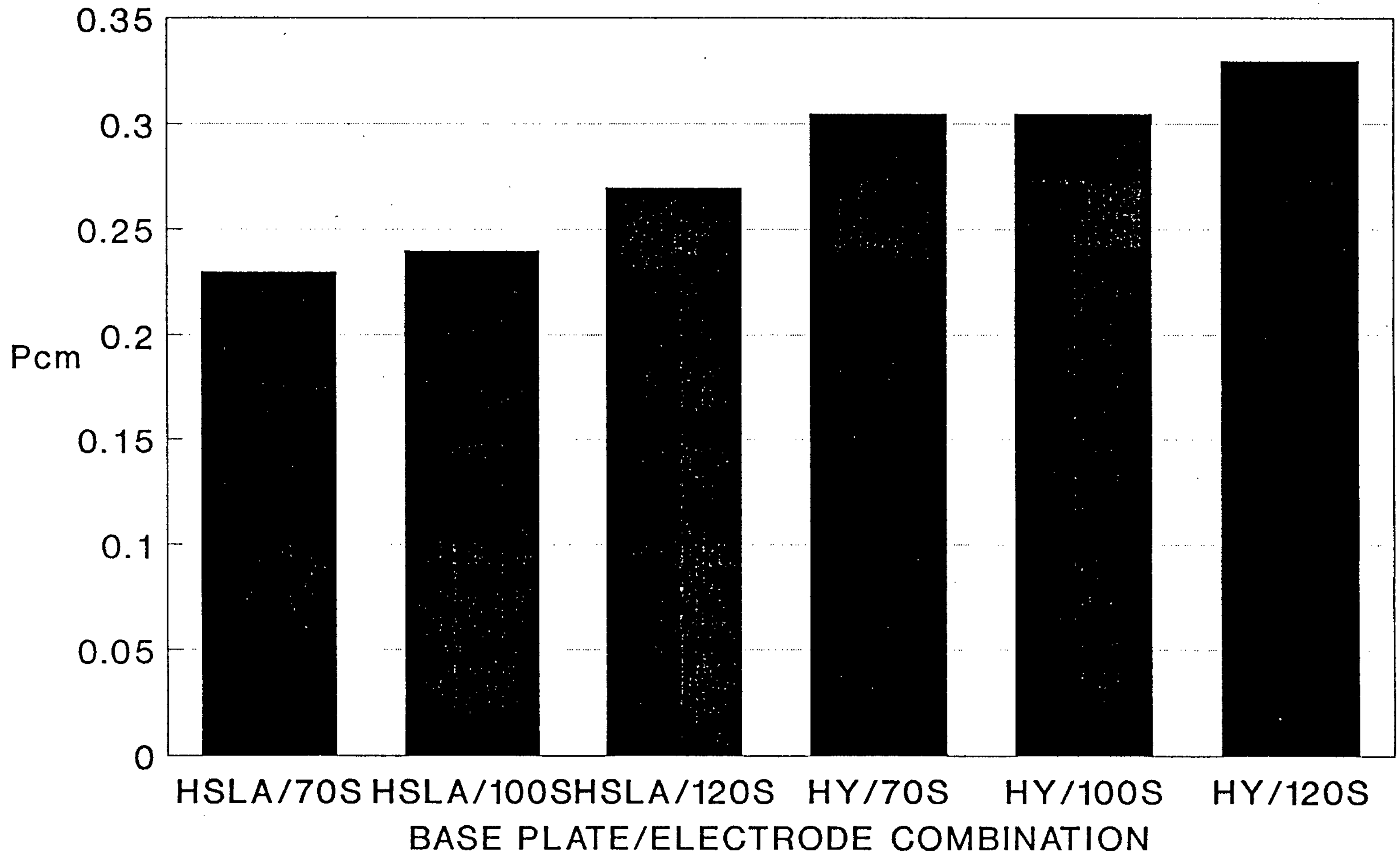
Completion: 1998, Q2


WELDABILITY MEYHODOLOGY
WELD DEPOSIT CHEMISTRY, Pcm
Pcm = C+(Mn+Cu+Cr)/20+Si/30+Ni/60+Mo/15+V/10+5*B
Pcm
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
HSLA/70S
HY/70S
HSLA/100S
HY/100S
HSLA/120S
HY/120S
BASE PLATE/ELECTRODE COMBINATION
CDNSWC

WELDABILITY MEYHODOLOGY

WELD DEPOSIT CHEMISTRY, Pcm

Pcm = C+(Mn+Cu+Cr)/20+Si/30+Ni/60+Mo/15+V/10+5*B



CDNSWC

WELDABILITY METHODOLOGY

RESULTS

- COMPARISON OF RESULTS TO PHA MODEL

$$t_{100,crit} = 1145 * P_{HA}^{2} + 864 * P_{HA} - 171$$

WHERE $P_{HA} = \mathrm{LOG}\,[A * Hd'] + F$

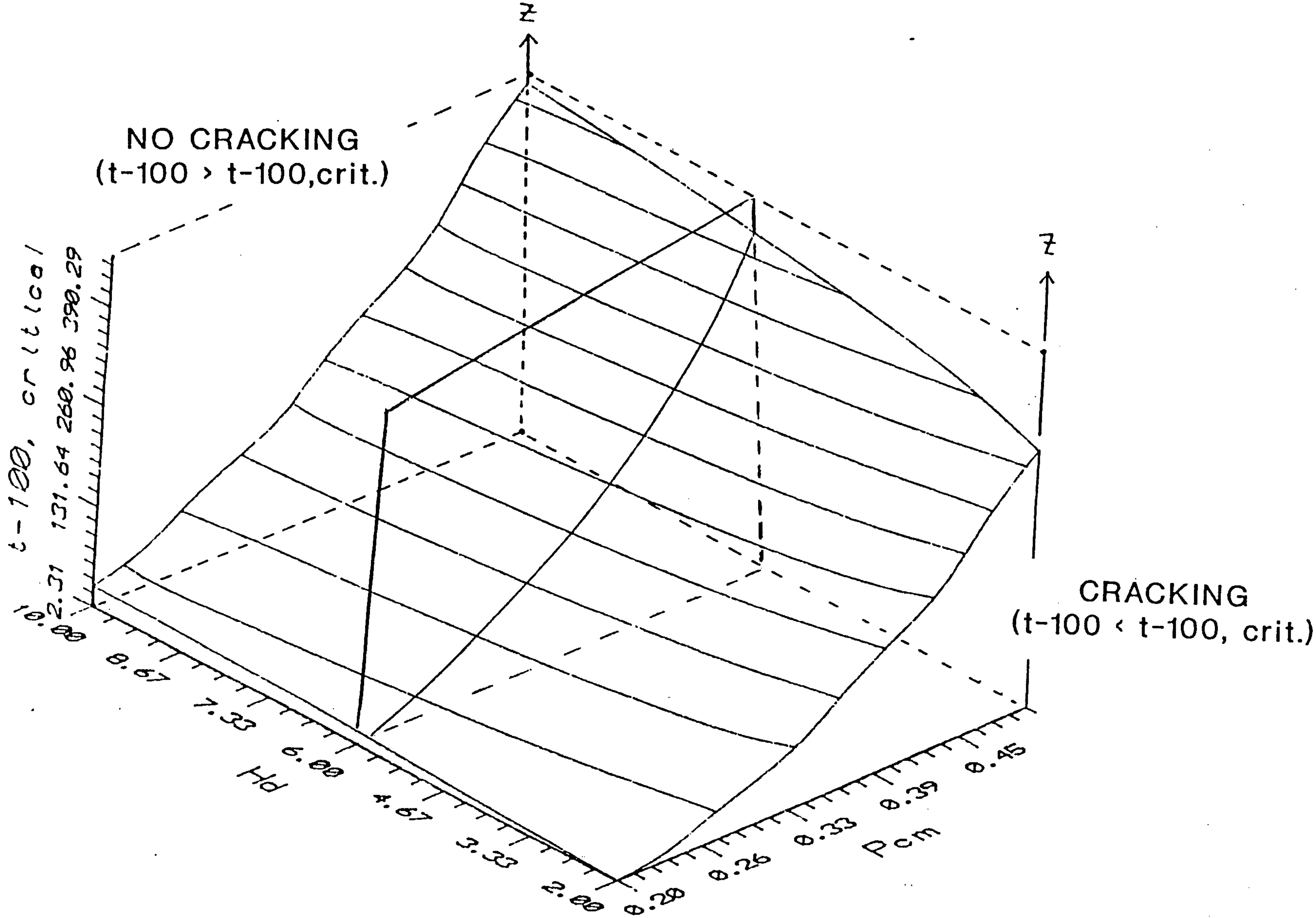
$F = 11.9 * P_{CM} + .000089\ R_{FY} - 2.55$

Hd'= Diffusible Hydrogen via glycerine method

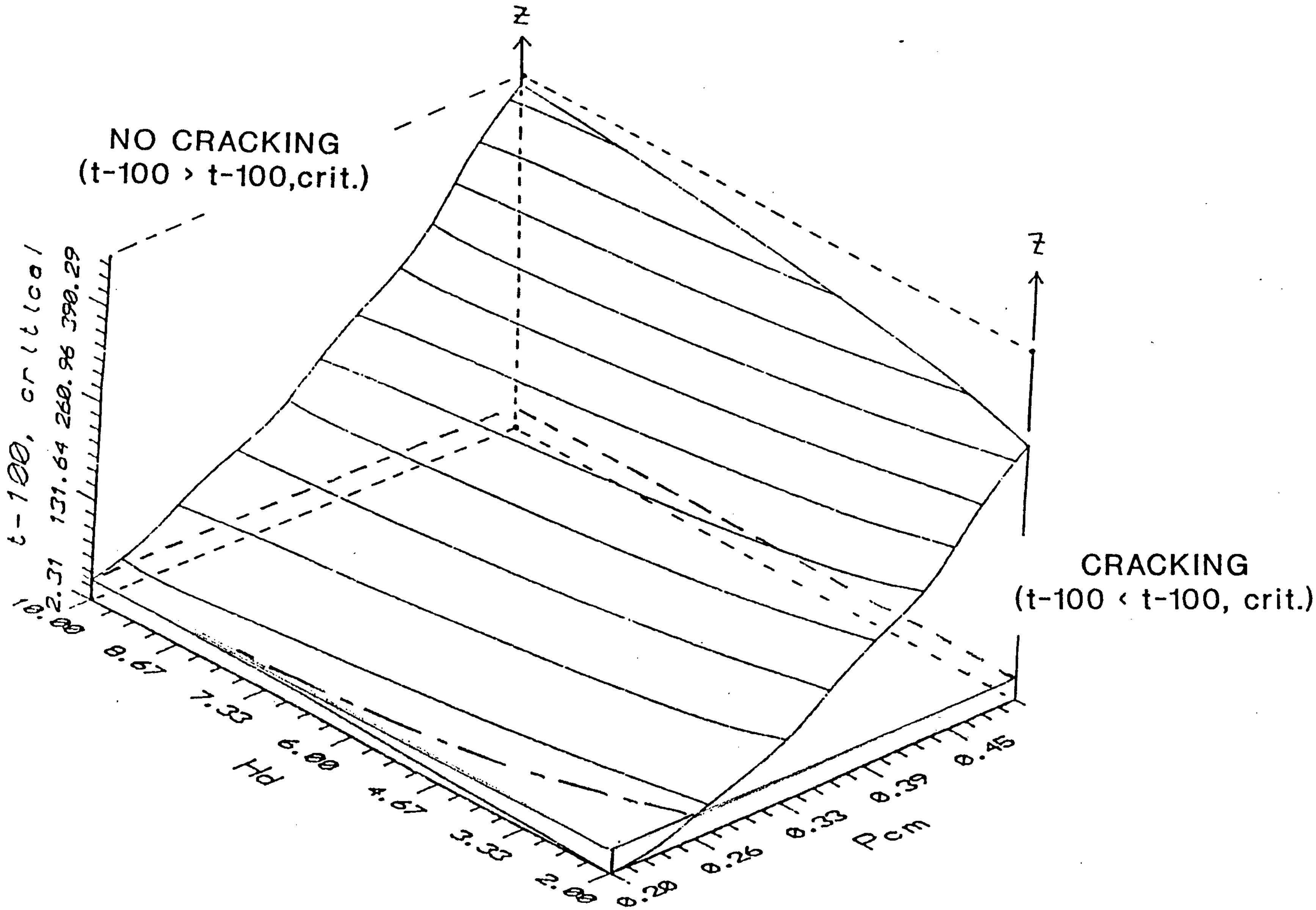
$(Hd' = .67\ Hd_{IIW} - .8)$

CDNSWC

WELDABILITY METHODOLOGY

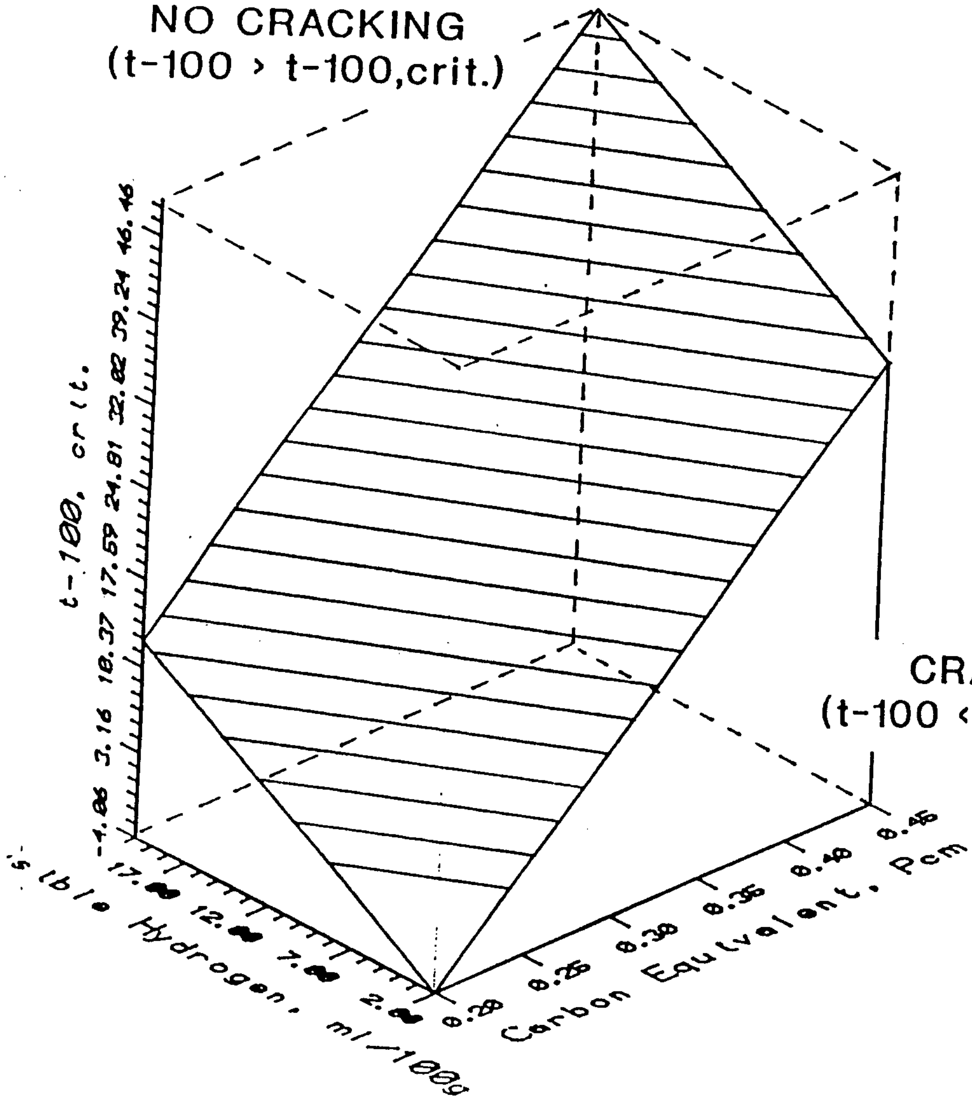


WELDABILITY METHODOLOGY



WELDABILITY METHODOLOGY

FY 92 RESULTS



t-100,crit = 148*Pcm +Hd/1.08 -30.5

where:

Pcm = C + (Mn+Cu+Cr)/20 + Si/30 + Ni/60 + Mo/15 + Nb/10 + 5*B

Hd = diffusible hydrogen (IIW)

CDNSWC

WELDABILITY METHODOLOGY
HOW CAN THE MODEL BE USED

SCENARIO 1

• A NEW CONSUMABLE IS DEVELOPED FOR WELDING HY-100 STEEL

WHAT PREHEAT TEMP. IS EXPECTED FOR WELDING 2-IN. THICK MATL. WITH A 75 kJ/in. HEAT INPUT ?

Pcm (WIRE) = .31
Pcm (HY-100) = .37
Pcm (ROOT PASS) = .34

Hd = 6 ml/100g

t-100,crit = 20 minutes
MIN. PREHEAT = 125 C (260 F)

SCENARIO 2

• WE WANT TO ELIMINATE PREHEAT FOR WELDING UP TO 1-IN THICK HSLA-100 STEEL, 75 kJ/in. H.I.

WHAT MAX. Pcm LEVEL IN THE WIRE EXPECTED TO BE REQUIRED FOR Hd LEVEL OF 4 ml/100g ?

Pcm (HSLA-100) = .27
Pcm (WIRE) = X
Pcm (ROOT PASS) = (.27+x)/2

Hd = 4 ml/100g

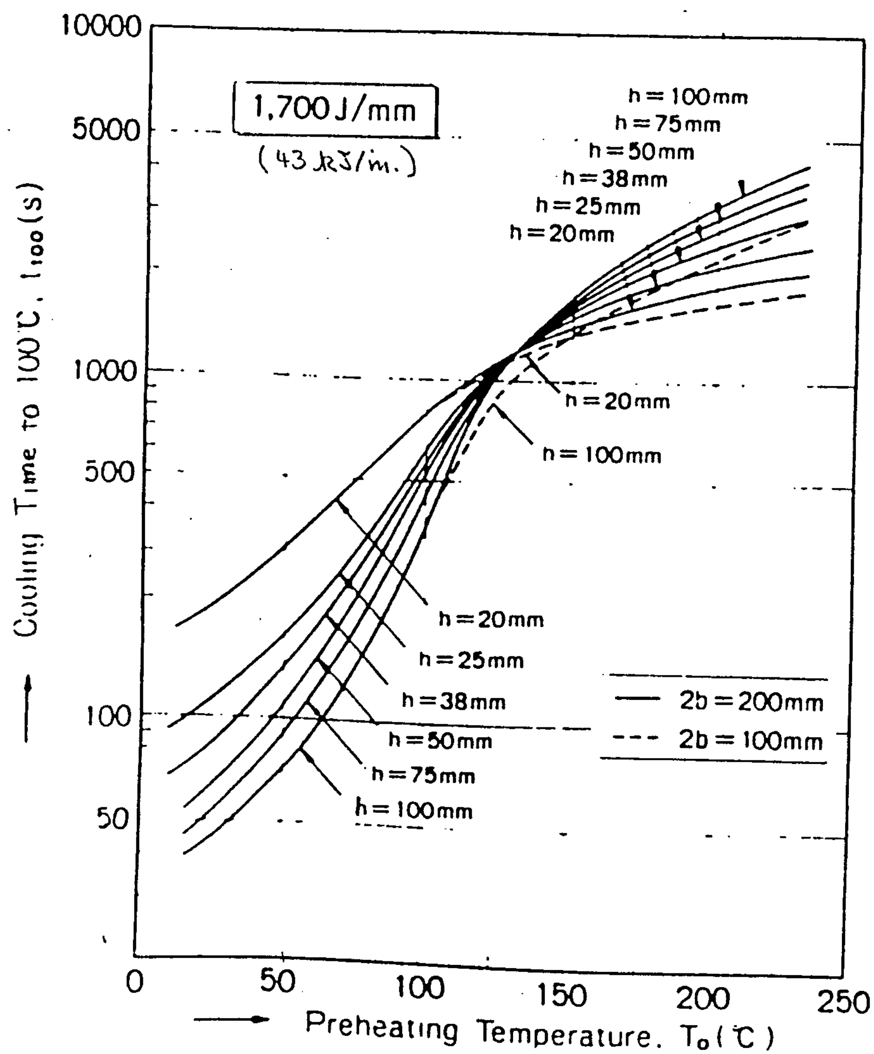
t-100 (=t-100;crit) = 5 min
MAX. Pcm (ROOT PASS) = .25

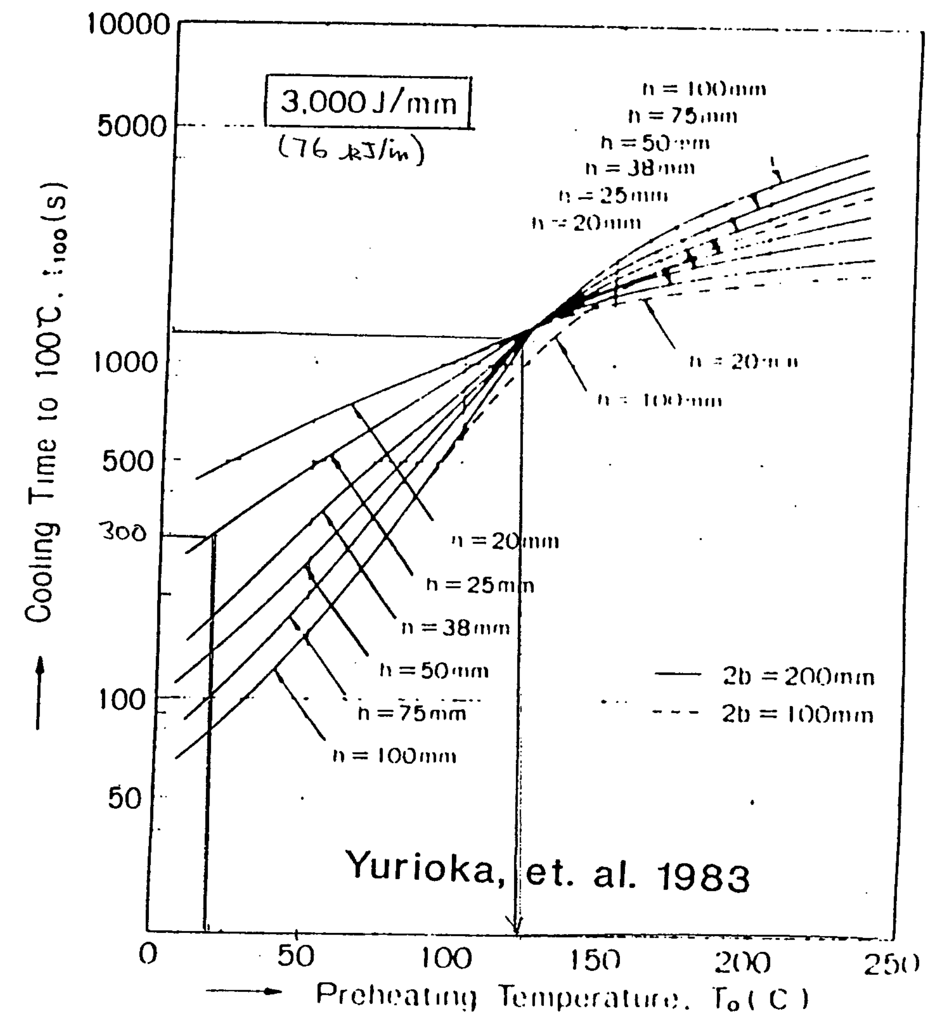
MAX. Pcm (WIRE), X = .23

CDNSWC

WELDABILITY METHODOLOGY

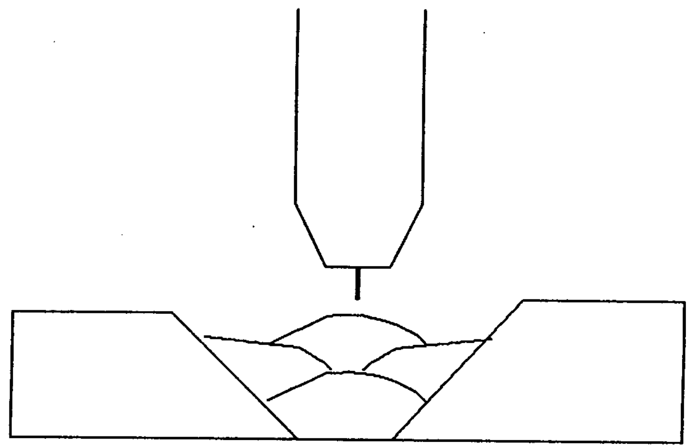
FY 92 RESULTS



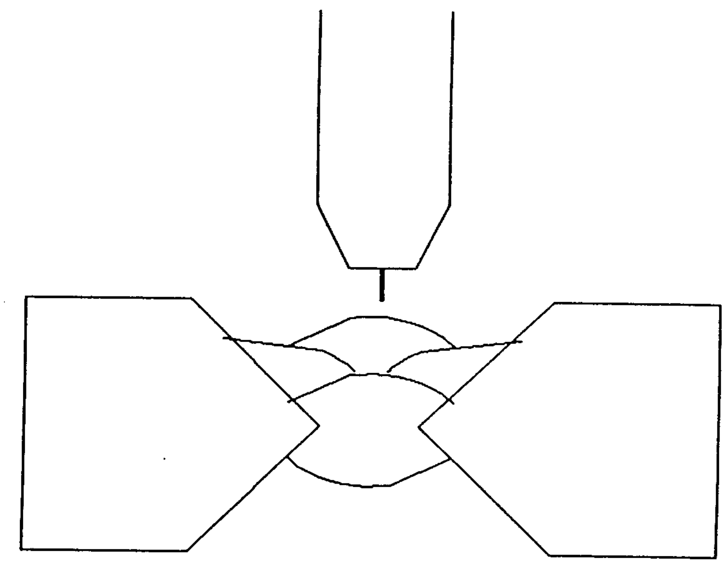


HSLA-100 CONSUMABLES DEVELOPMENT

GMAW WIRE DEVELOPMENT - WELDING CONDITIONS



3/4" THICK HSLA-100
55 kJ/in, 300 P/I
15 F/s CALCULATED COOLING RATE

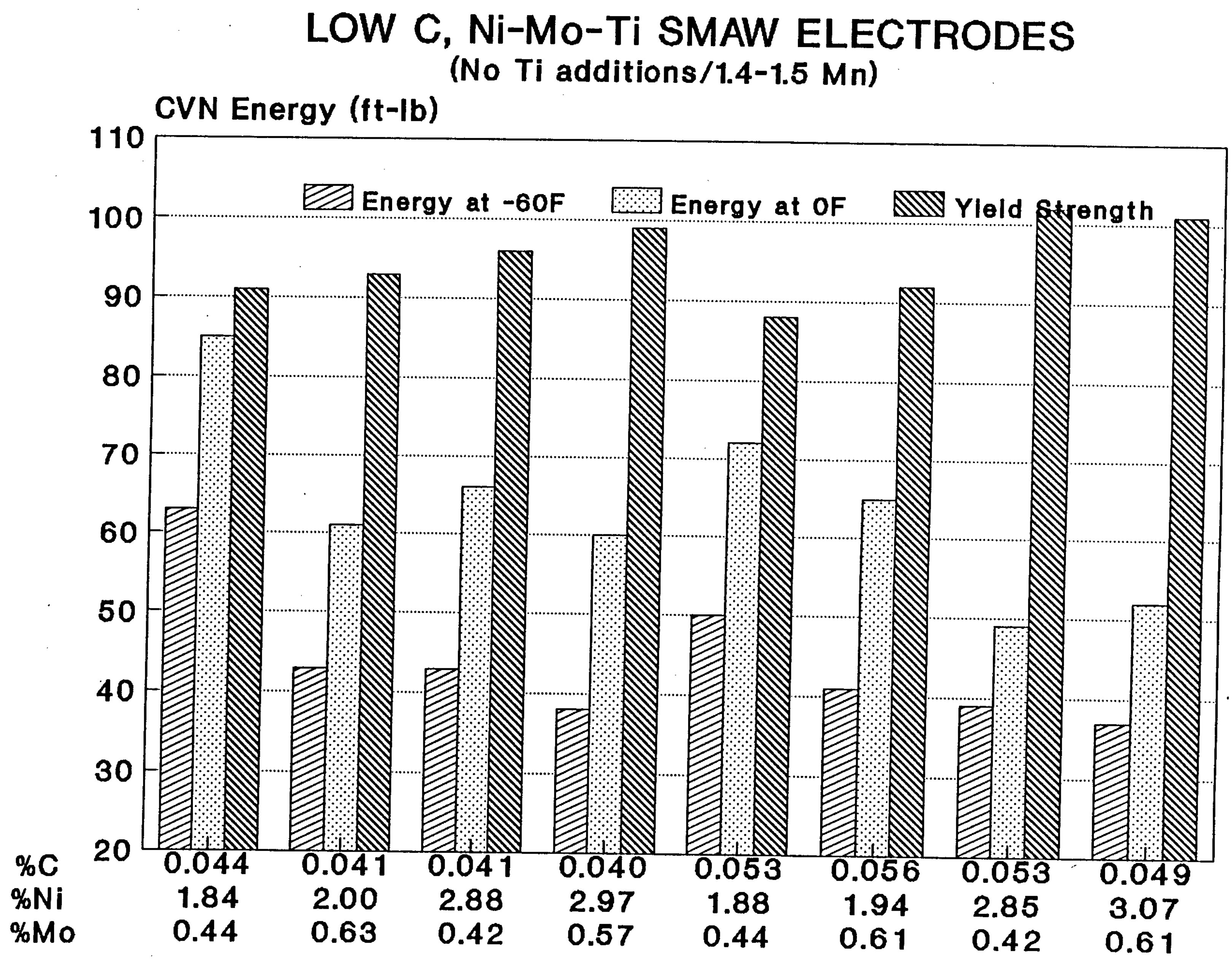


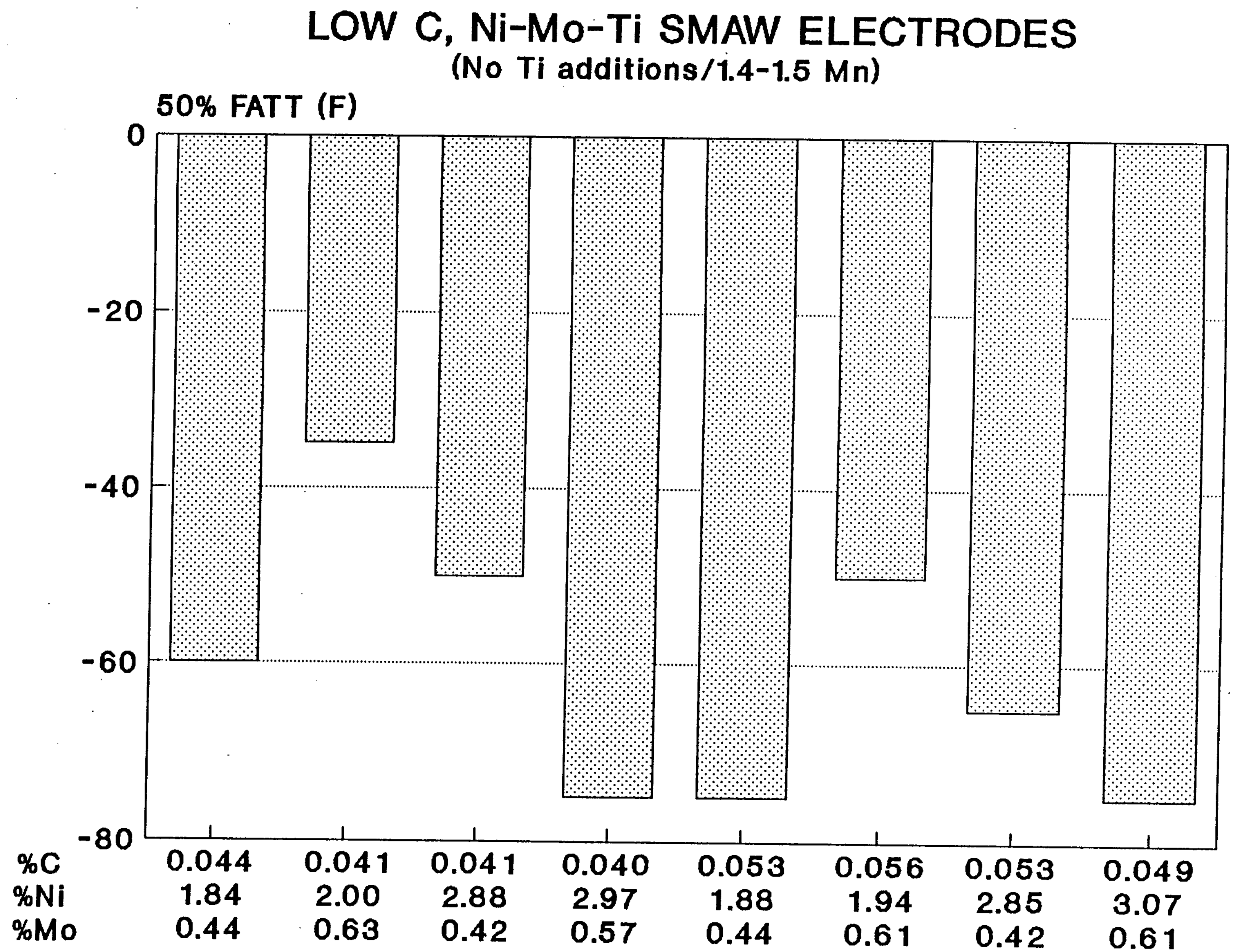
2" THICK HSLA-100
30-35 kJ/in, 70-75 P/I
90 F/s CALCULATED COOLING RATE

TARGET WIRE COMPOSITIONS:

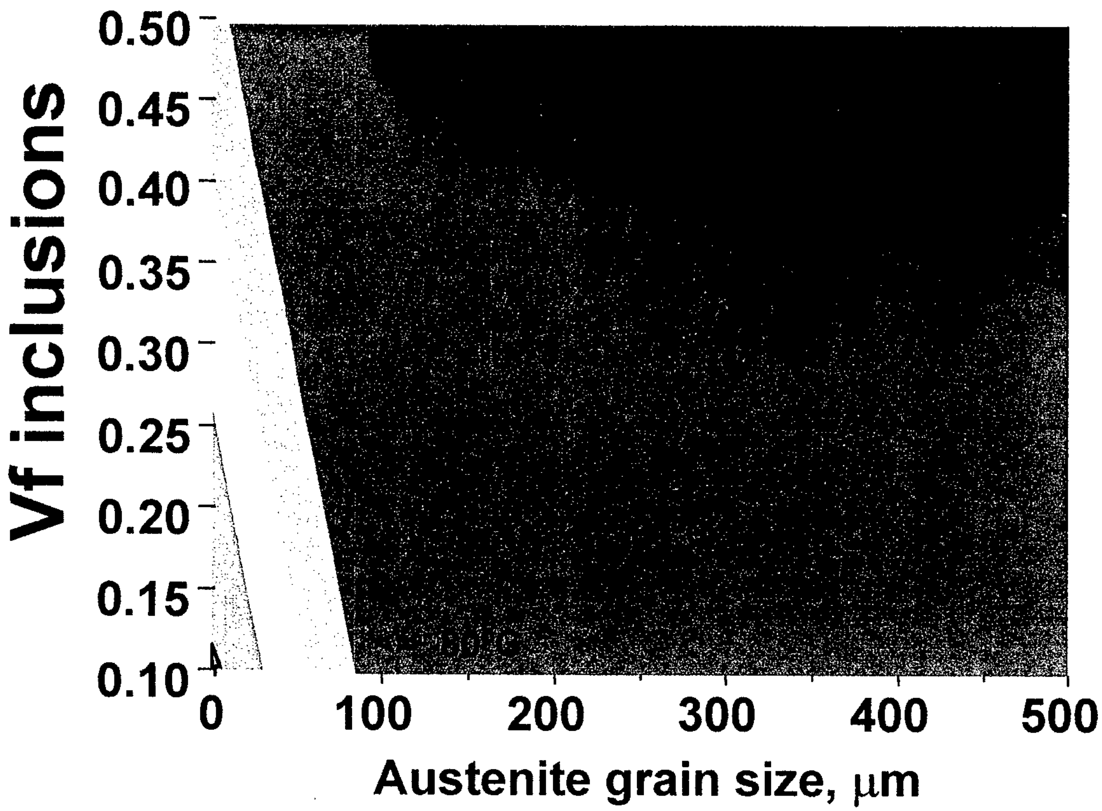
HEAT B:	*0.04C*	*1.9Mn*	*3.3Ni*	*0.5Mo*	*0.025Ti*
HEAT C:	*0.04C*	*1.9Mn*	*3.3Ni*	*0.6Mo*	*0.025Ti*
HEAT D:	*0.06C*	*1.9Mn*	*3.3Ni*	*0.6Mo*	*0.025Ti*
HEAT A:	*0.04C*	*1.9Mn*	*3.0Ni*	*0.5Mo*	*0.025Ti*

CDNSWC


LOW C, Ni-Mo-Ti SMAW ELECTRODES
(No Ti additions/1.4-1.5 Mn)
CVN Energy (ft-lb)
110
100
90
80
70
60
50
40
30
20
Energy at -60F
Energy at 0F
Yield Strength
%C
%Ni
%Mo
0.044 1.84 0.44
0.041 2.00 0.63
0.041 2.88 0.42
0.040 2.97 0.57
0.053 1.88 0.44
0.056 1.94 0.61
0.053 2.85 0.42
0.049 3.07 0.61


LOW C, Ni-Mo-Ti SMAW ELECTRODES
(No Ti additions/1.4-1.5 Mn)
50% FATT (F)
0
-20
-40
-60
-80
%C
%Ni
%Mo
0.044 1.84 0.44
0.041 2.00 0.63
0.041 2.88 0.42
0.040 2.97 0.57
0.053 1.88 0.44
0.056 1.94 0.61
0.053 2.85 0.42
0.049 3.07 0.61

50% FATT MODEL



50%FATT =

$-151+135V_f-21\ln(\gamma)^{-0.5}$

where,

V_f = Vol. % incls.

γ = Aust. grain width

Task 3, Activity 2 Development of ULC Wires

Task 3: Development of High Strength Steel Filler Metals

Activity 3: Ultra Low Carbon (ULC) Wire Evaluation

Organization: USA-NSWCCD

Description: The objective is to evaluate and certify an 80 ksi yield strength wire that can be welded at preheat levels down to 60 ^{0}F. Evaluation will included mechanical property testing over a wide range of cooling rates, as well as weldability, fatigue, SCC, and dynamic fracture testing. Microstructural and chemical analyses will be performed to provide metallurgical rationale for observed properties. Shipyard fabrication studies will be performed to assess performance under stringent production conditions.

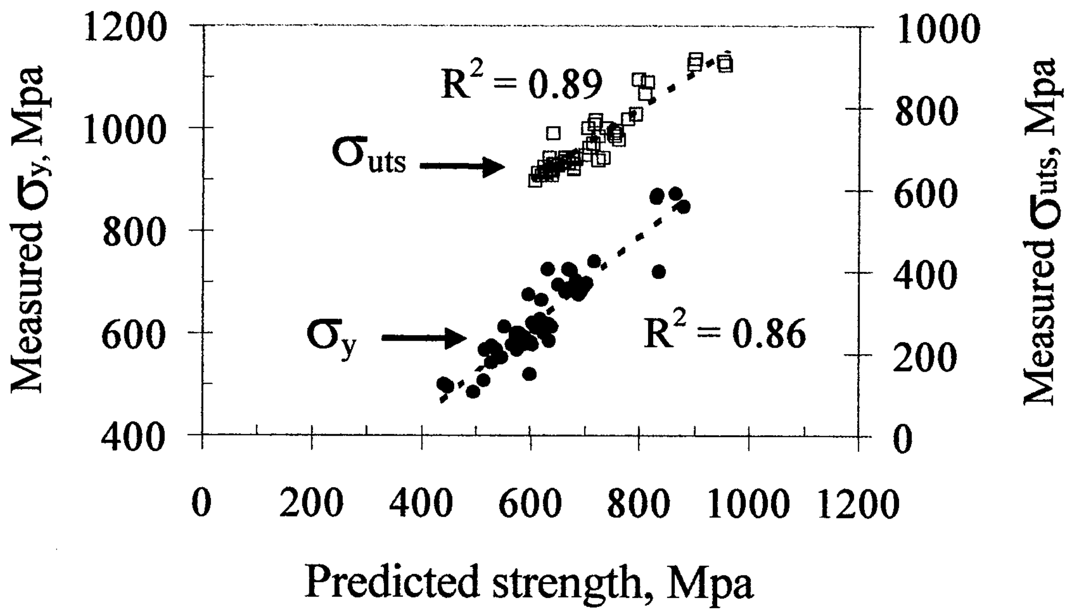
Results: Mechanical property and weldability evaluation of final matrix of 4 experimental wires (named Alloys 1-4) is complete. All wires met mechanical property requirements. 3 of 4 wires met weldability goals. Explosion crack starter testing was successfully completed on Alloy 2. A 25,000-lb prototype production heat, based on Alloy 2 has been melted in production. The first lot of wire (approx. 6000 lb) will be delivered in Jan 99. Wire will then be available for round robin testing. Quantities available for round-robin will be determined by the U.S. Working Group. This work was presented at the PRICM 3 conference on 13-16 July 1998. A copy of this paper will be forwarded with the final TTCP report.

Plans: U.S. Navy (including NSWCCD and U.S. shipyards) evaluation of the prototype production heat will begin in Jan 99. Round robin testing by Task 3 participants can begin as soon as test facilities and available quantities are determined.

Status: in progress

Completion: 2001, Q4

Strength Models



If $T_{50} \leq 510°C$, $\sigma_{uts} = 1332 - 1.38*T_{50} + 61*C*dT/dt$

If $T_{50} > 510°C$, $\sigma_{uts} = 890 - 0.48*T_{50}$

$\sigma_y = 1297 + 14*t - 1.2*T_{50} - 48*\gamma_{gw}$

Where,

σ_y = 0.2% offset yield strength, Mpa,

σ_{uts} = ultimate tensile strength, Mpa,

t = plate thickness, cm,

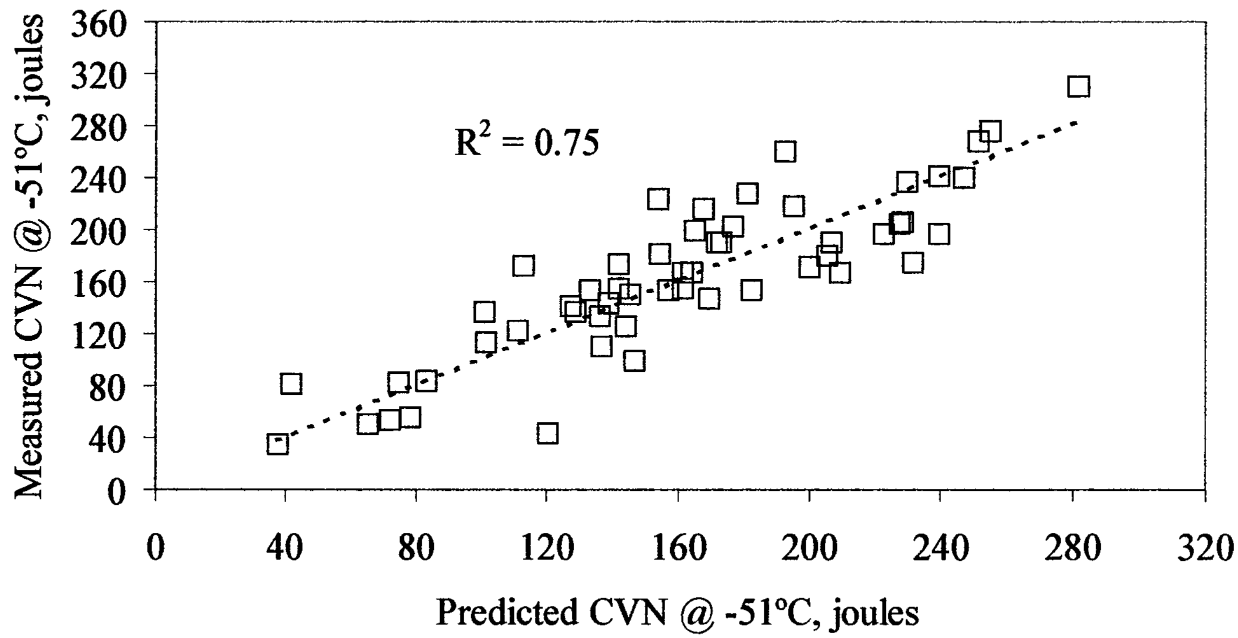
dT/dt = calculated cooling rate at 538°C, °C/s,

γ_{gw} = austenite grain width, microns and,

C = Carbon content, wt.%.

Task 3, Activity 2 Development of ULC Wires

Toughness Model



$$\ln CVN = -0.16t + 0.47\ln(dT/dt) + 3.8(\sigma_y / \sigma_{uts}) + .06(Si/O) - 0.45(C*dT/dt)$$

Where,

σ_y = 0.2% offset yield strength, Mpa,

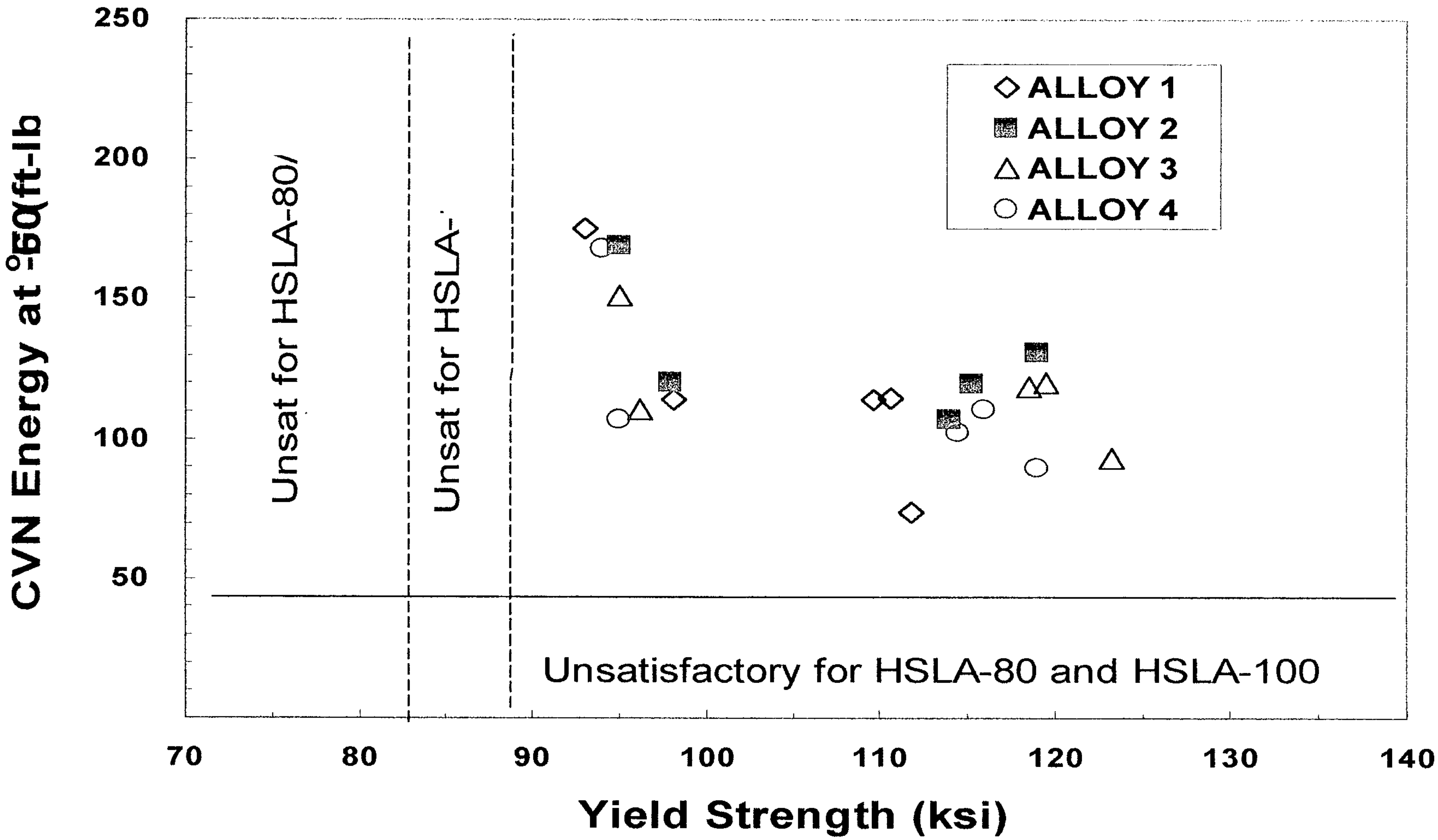
σ_{uts} = ultimate tensile strength, Mpa,

t = plate thickness, cm,

dT/dt = calculated cooling rate at 538°C, °C/s,
C = Carbon content, wt.%.

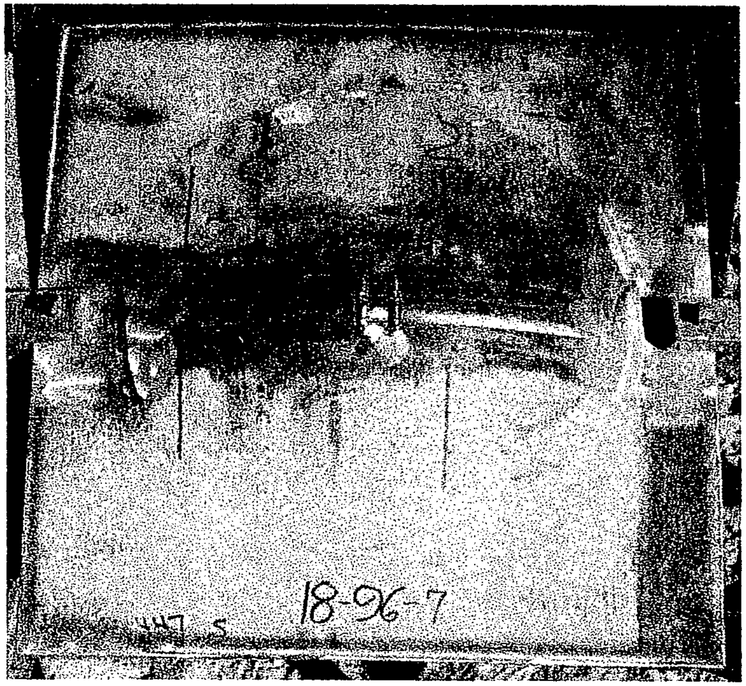
Task 3, Activity 2 Development of ULC Wires

Strength and Toughness Characteristics of Alloys 1-4



Task 3. Activitv 3. ULC Wire Evaluation

Phase 3 Crack Starter Bulge Tests



Alloy 2 was selected as best candidate for scale up. Prior to purchasing a production heat, the dynamic fracture resistance of Alloy 2 was successfully evaluated using the explosion crack starter test.

Alloy 2
2-in. HY-100 plate
0°F test temperature
Each specimen received 2 shots
- 7.1, 7.5% reduction-in-thickness
- 6.8, 6.6% reduction-in-thickness

Top and Side Views of Specimen 18-96-7

Task 3, Activity 3, ULC Wire Evaluation

Task 3: Development of High Strength Steel Filler Metals

Activity 4: Evaluation of ULCB MCA Welding Consumables

Organization: USA-NSWCCD
Australia-DSTO

Description: This activity will evaluate four MCA welding wires produced to meet weld deposit compositions specified by NSWCCD. Following discussions with NSWCCD, further "preheat free" formulations for both manual metal arc and flux-cored arc consumables have been evaluated by DSTO. All consumables delivered acceptable welding characteristics with a stable arc, easy slag removal and satisfactory bead appearance. Most of the experimental weld metals met our minimum yield strength of 690 MPa. In general Charpy toughness was quite poor and did not meet our objective of 64J @ -51C. Subsequent metallographic examination showed that unexpectedly high proportions of unrefined primary structure may have contributed to this poor result. Further work is underway investigating this aspect.

DSTO is now in a position to participate in round robin testing of selected NSWCCD preheat-free consumables using 690 MPa yield QT microalloy steel as the base material.

Results: Four selected MCA wire compositions were prepared into welding wire and evaluated.

Plans: NA

Status: in progress

Completion: 2001, Q3

Table V. Typical Weld Metal Analyses from Rich and Lean Variants of ED1

Alloy	C	Mn	Si	Ni	Mo
Alloy 1	0.03	1.5	0.30	2.7	0.6
Alloy 2	0.03	1.7	0.30	2.7	0.6
Alloy 3	0.03	1.7	0.30	2.7	0.7
Alloy 4	0.025	1.5	0.30	3.0	0.6
Alloy 4	0.025	1.4	0.25	2.6	0.5

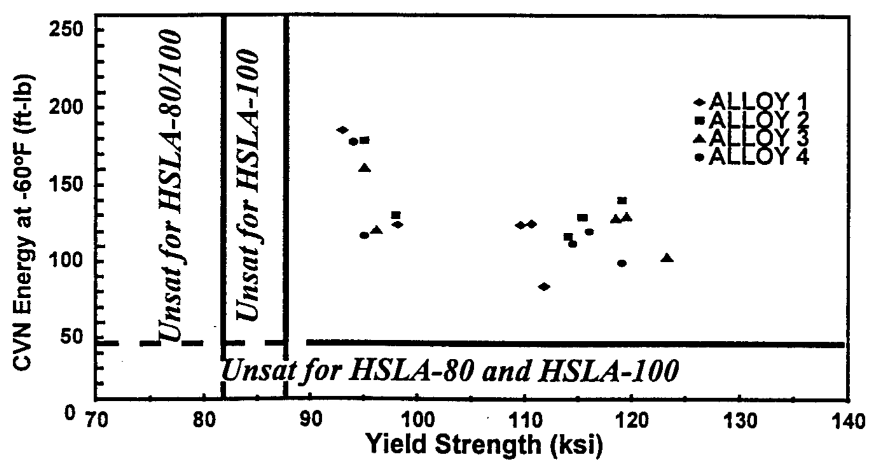


Figure 4. Yield Strength and CVN Toughness of Alloys 1-4.

Task 3: Development of High Strength Steel Filler Metals

Activity 5: Use of Fluorine and Optimal Oxygen Additions to the Welding Plasma to Assist in Hydrogen Management

Organization: USA-CSM

Description: The use of selected fluoride and oxide additions to welding consumables to promote a plasma chemistry that reduces the weld pool hydrogen content is being investigated.

Results: Effective use of the water and HF reactions in the plasma to reduce weld pool hydrogen content has been demonstrated. Various fluoride additions are being added to the electrode covering and the resulting welds are being evaluated. Fluorides are being carefully selected based on their physical stability and their predicted pyrochemical behavior.

Further characterization of the influence of specific fluoride additions on the resulting diffusible hydrogen content has been performed. With the determination of the most promising fluoride additions more extensive evaluation will be preformed to determine the optimum fluoride content and weld metal oxygen content necessary for various sets of welding parameters. Diffusible hydrogen contents have been dropped from 5 ml/100 gram of Fe to 1.5 ml/100 gram of Fe, a significant reduction. The best fluorides determined from present effect are $AlSiF_2$ and KF.

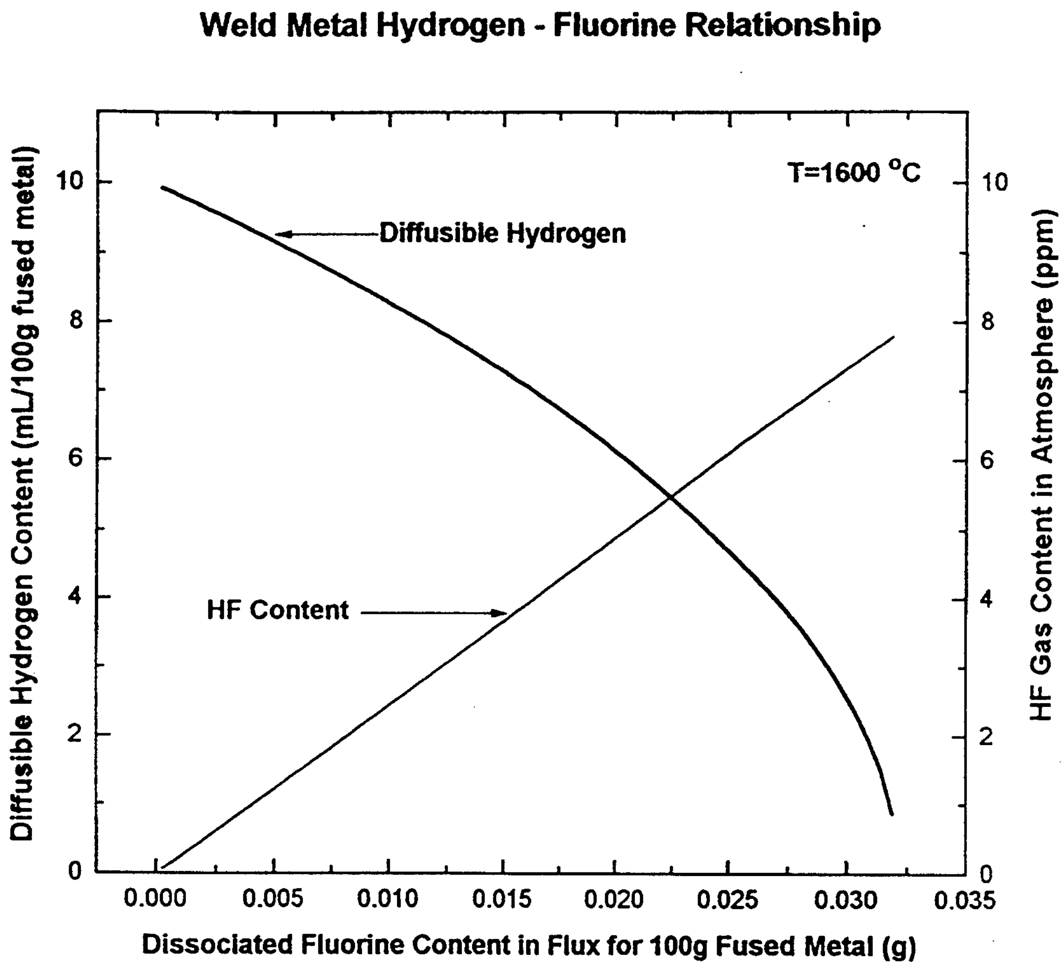
Plans: NA

Status: in progress

Completion: 1999, Q3

Thermo-chemical Reaction in Arc Plasma

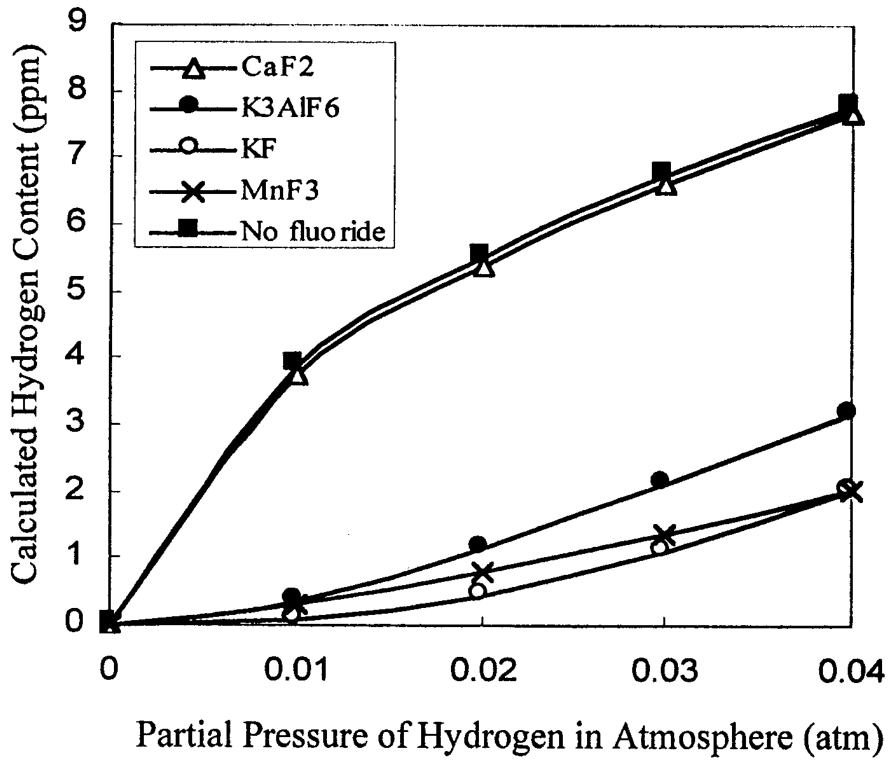
Hydrogen absorption control by hydrogen - fluorine reaction



- $H_2\,(g) + F_2\,(g) = 2\,HF\,(g)$
  - $k = \exp(-\Delta G^0/RT) = \dfrac{(P_{HF})^2}{P_{H_2} \cdot P_{F_2}}$
- $H_2\,(g) = 2\,\underline{H}$

Methodology of Investigation

Calculation of the Effectiveness of K_3AlF_6, MnF_3, and KF

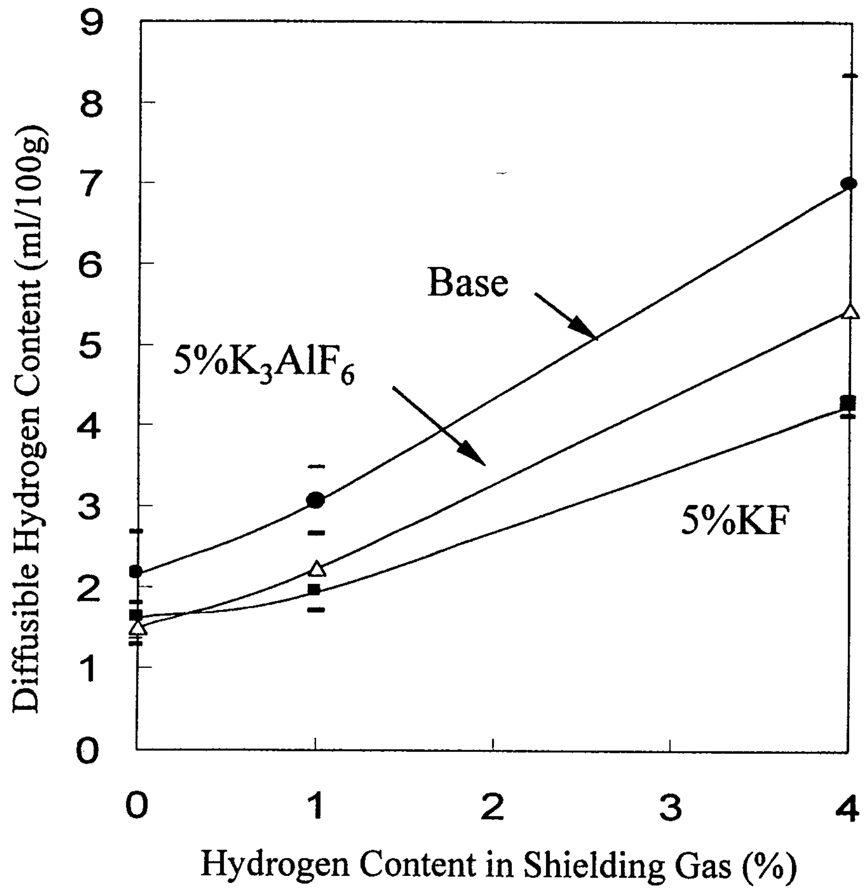


Calculated Hydrogen Content in Liquid Iron at 2050°C as a Function of Partial Pressure of Hydrogen

M. Matsushita and S. Liu, *"Hydrogen Control in Steel Weld Metal by Means of Fluoride Additions in FCAW,"* presented at the 79th Annual AWS Convention, Detroit, MI, April 26-31 (1998)

Methodology of Investigation

Experimental Verification of Effectiveness of K_3AlF_6 and KF

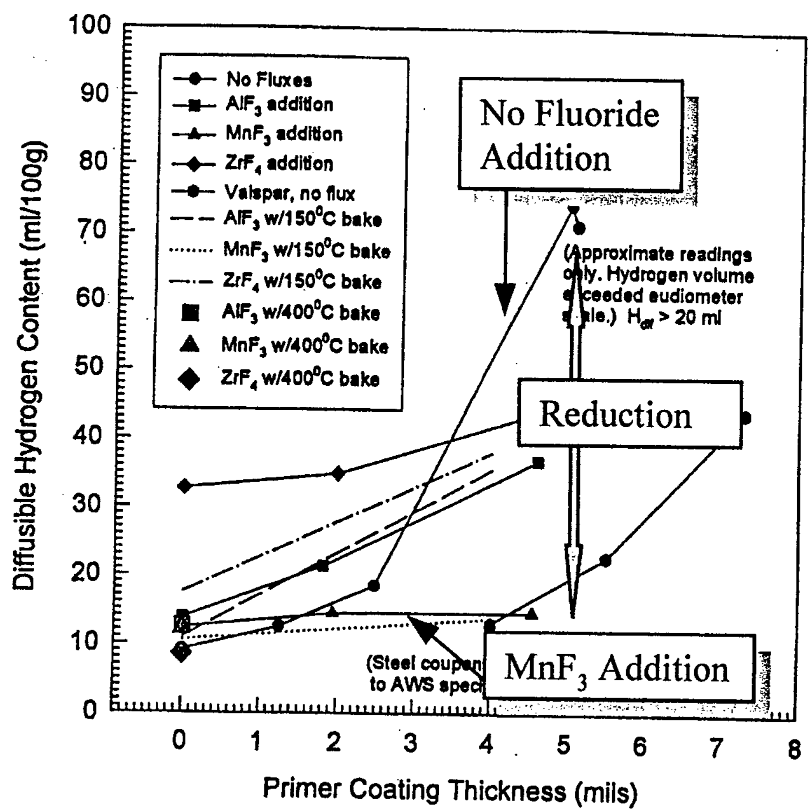


Experimental Results of Diffusible Hydrogen Levels with Additions of Fluorides

M. Matsushita and S. Liu, *"Hydrogen Control in Steel Weld Metal by Means of Fluoride Additions in FCAW,"* presented at the 79th Annual AWS Convention, Detroit, MI, April 26-31 (1998)

Methodology of Investigation

Experimental Verification of Effectiveness of MnF_3

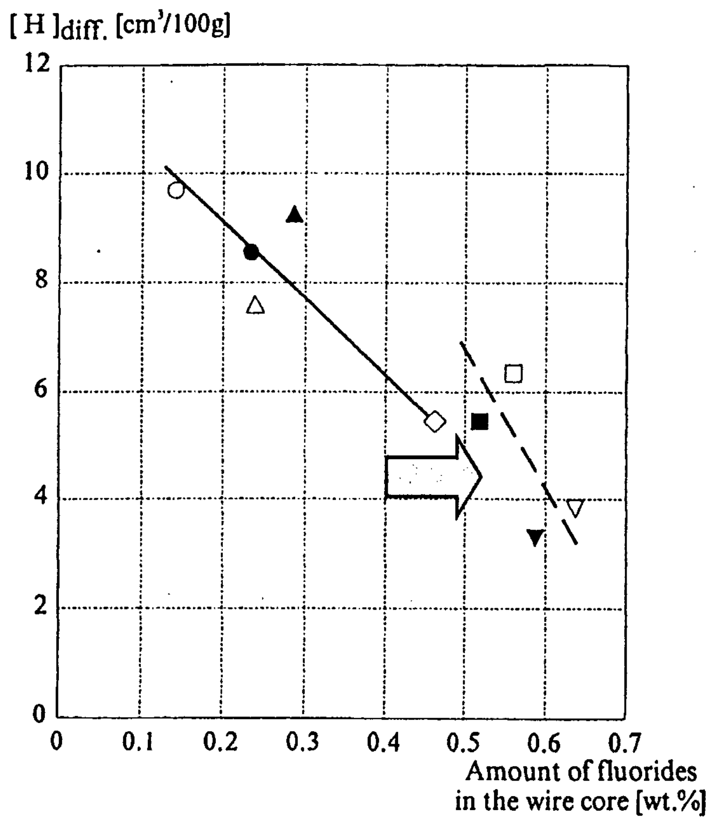


Effect of Primer Thickness, Primer Type, and Fluoride Additions on Weld Metal Diffusible Hydrogen Content

K. S. Johnson, *"Diffusible Hydrogen Control and Microstructure Refinement in FCA Welds Performed over Primer-Coated Steels,"* Graduate Thesis, T-5098, (1998)

Methodology of Investigation

Effectiveness of Complex Fluorides



○ - MgF_2
● - CaF_2
△ - NaF
▲ - KF
◇ - ZrF_4

■ - Na_2SiF_6
□ - Na_2TiF_6
▼ - K_2SiF_6
▽ - K_2TiF_6

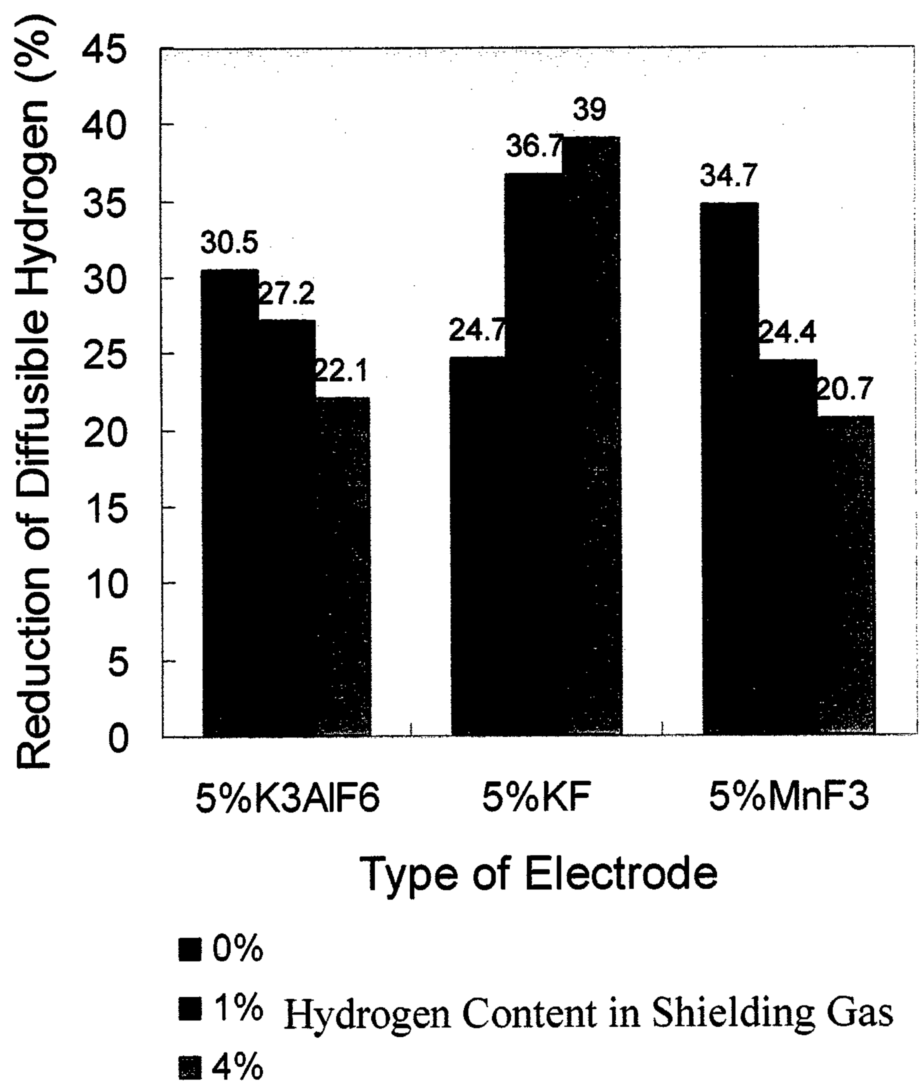
Plot of Diffusible Hydrogen Content in Deposited Metal vs. Amount of Fluorides in the Wire Core
(content of fluoride being constant) (Ref. 14)

I. K. Pokhodnya, *"Hydrogen Behavior in Welded Joints,"* E. O. Paton Electric Welding Institute, National Academy of Sciences of Ukraine, Ukraine, Kiev, (1996)

Experimental Verification

Result

Reduction of diffusible hydrogen from the levels given by Base electrode established with 5%K_3AlF_6, 5%KF and 5%MnF_3 wires



Task 3: Development of High Strength Steel Filler Metals

Activity 6: Use of Austenitic Decomposition Start Temperatures to Predict Weld Hydrogen Distribution and Cracking Behavior

Organization: USA-CSM
USA-NSWCCD

Description: A practice of comparing calculated austenitic decomposition start temperatures of the base metal and weld metal to predict the hydrogen distribution and cracking behavior of high strength steel welds has been demonstrated. The practice uses the differences of the calculated martensite temperatures to predict whether cracking will occur in the weld or heat affected zone. The successful application of this indicator results from the large differences in hydrogen solubility and diffusion coefficient between ferrite (martensite)and austenite.

Results: Preliminary results indicate that this analytical approach can qualitatively make predicts of weld hydrogen behavior.

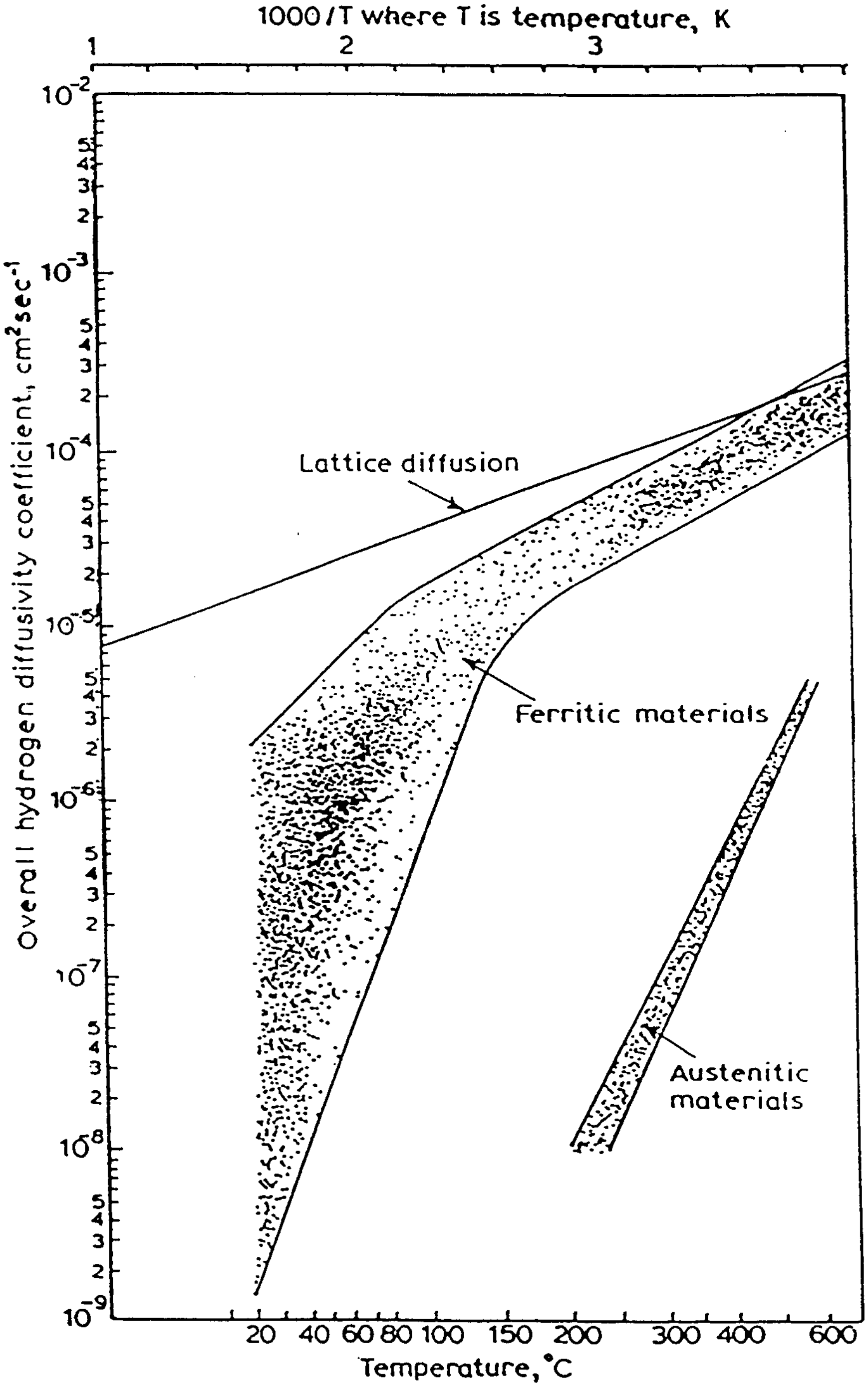
CSM has identified retained austenite is a significant factor in hydrogen management. Retained austenite in high strength steel weld is a high capacity high temperature bulk hydrogen trap. Retained austenite may transform to martensite with changes in service temperature and plastic strain, which can cause hydrogen release and resulting in cracking.

Plans: Efforts to refine this proposed practice will proceed. Work will expand the range of steel compositions of both plate materials and welding consumables used in this analysis to achieve more quantitative correlation. The thermomechanical simulator (Gleeble) will be used to determine measured austenitic decomposition start temperatures for the various high strength steel plates and weld deposits (welding consumables) of interest. Efforts will be made to promote welding consumable manufacturers to test this proposed practice.

Plans: NA

Status: completed

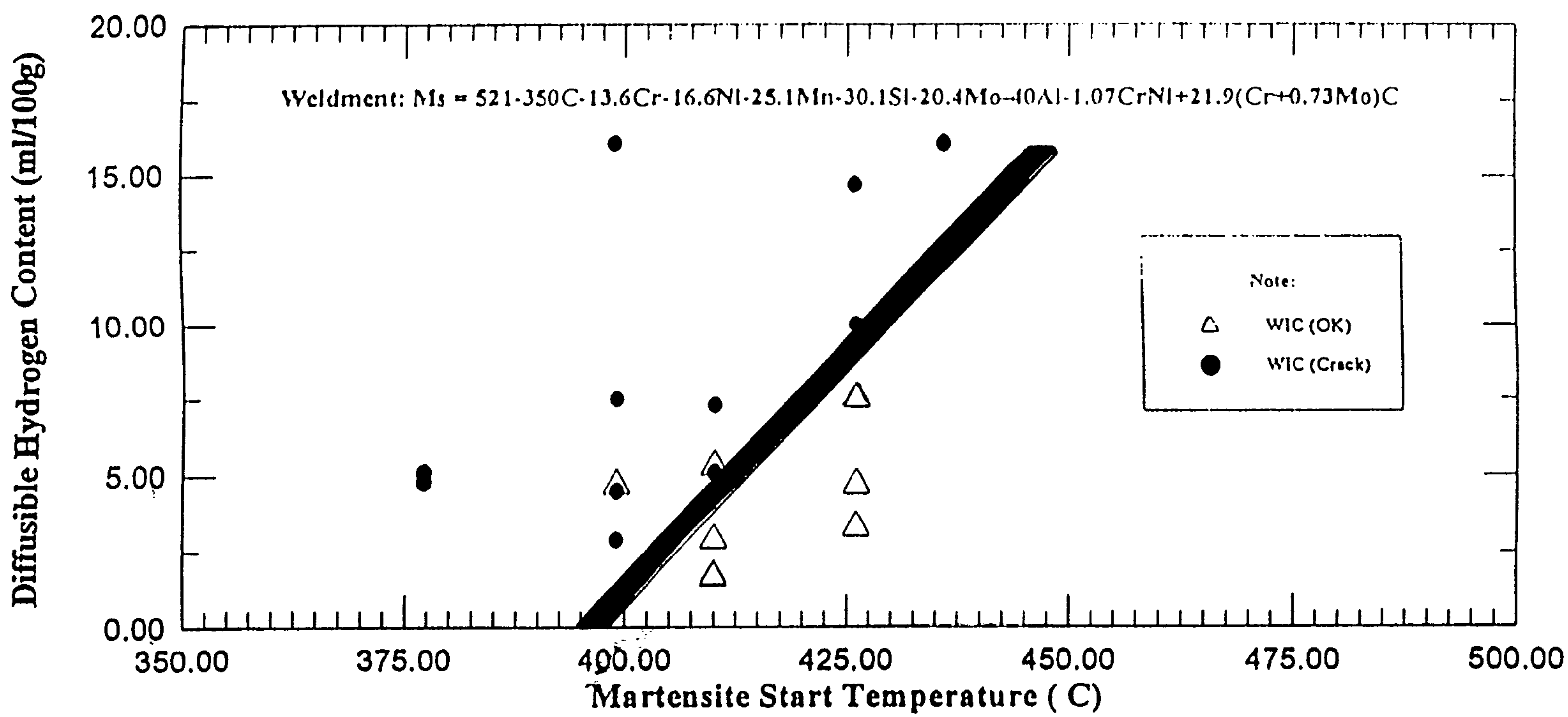
Completion: 1998, Q3

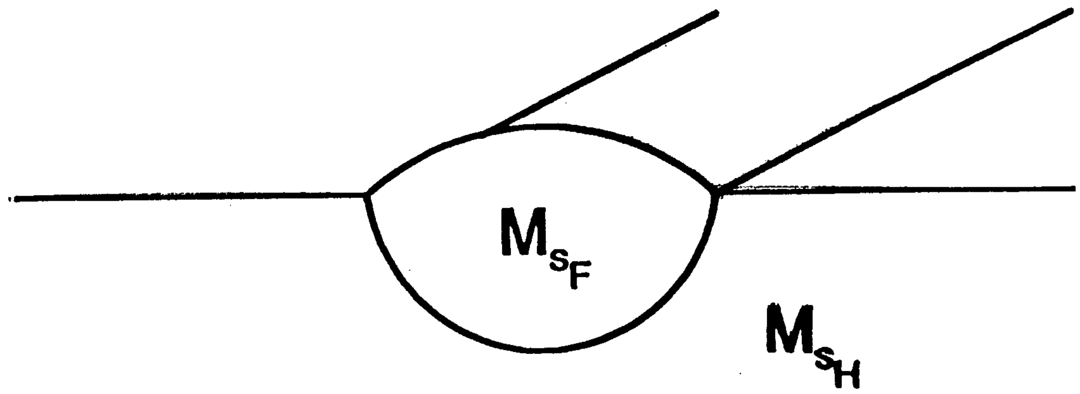


1000/T where T is temperature, K
1
2
3
Overall hydrogen diffusivity coefficient, $cm^2 sec^{-1}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Lattice diffusion
Ferritic materials
Austenitic materials
20 40 60 80 100 150 200 300 400 600
Temperature, °C

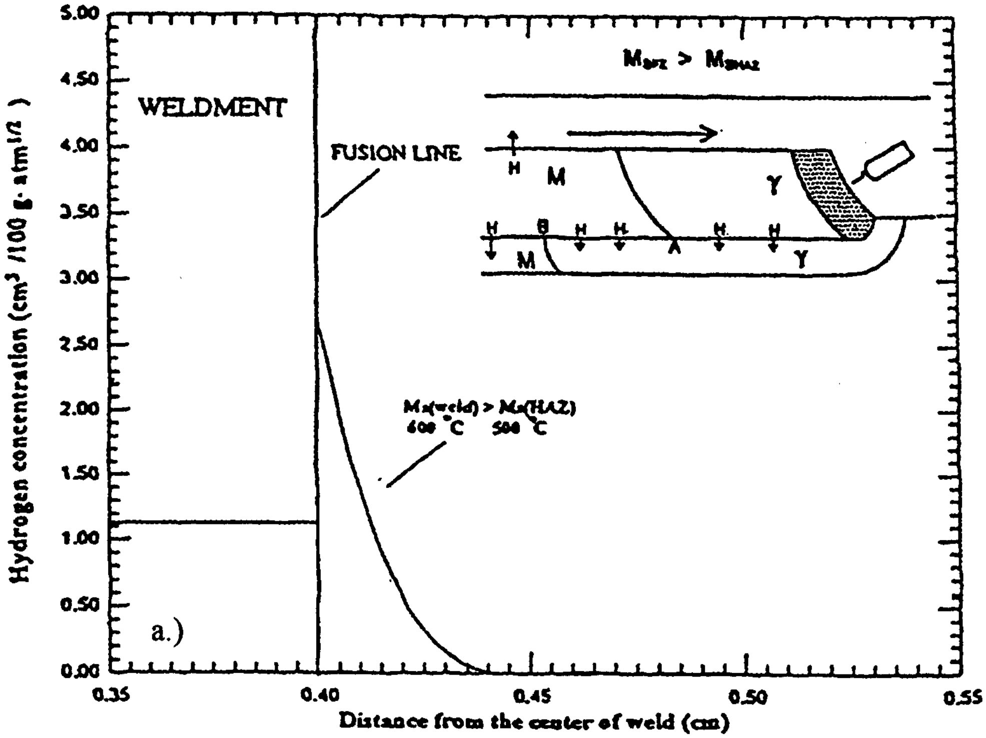
Hydrogen Diffusion

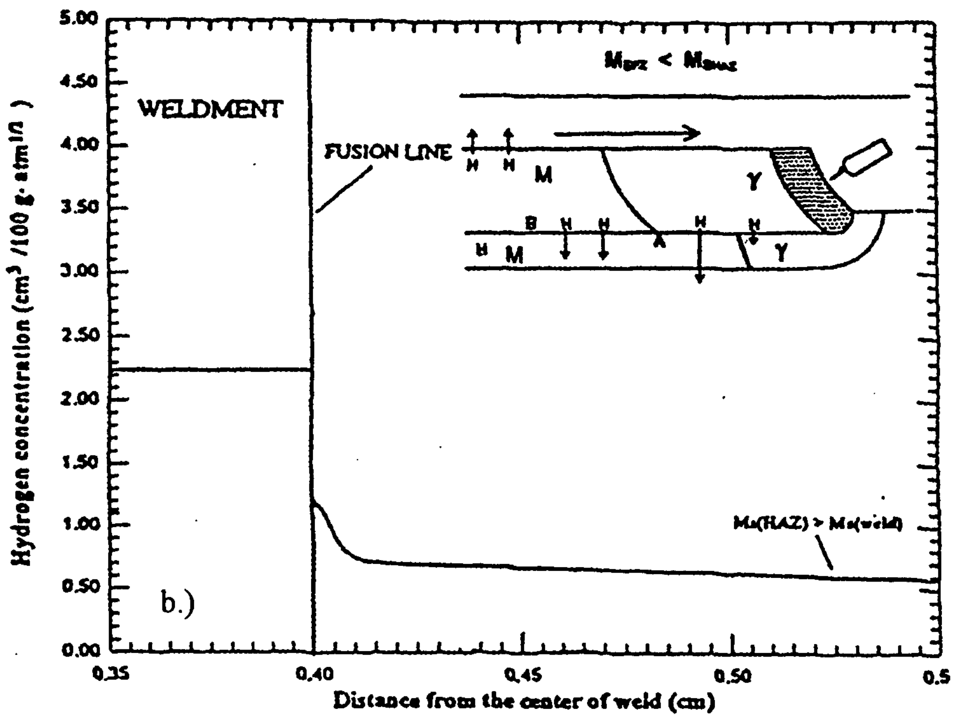
- Illustration of Hydrogen Cracking/Uncracking Zones by Hydrogen content and Martensite Start Temperature





<u>two cases:</u>	<u>crack location</u>
$M_{s_F} > M_{s_H}$	HAZ
$M_{s_F} < M_{s_H}$	FZ





Hydrogen distributions across the fusion line of a steel weldment for a.) Ms (weld) > Ms, b.) (HAZ) and Ms (weld) < Ms (HAZ)

Task 3: Development of High Strength Steel Filler Metals

Activity 7: Multipass Weld Metal Properties

Organization: Australia-CISRO
USA-CSM

Description: A cooperative research project between CISRO and CSM is in progress to better understand the influence of alloying additives on the microstructural and mechanical properties of weld metal for flux and metal cored welding. The work is proceeding at each institution and visitations have been made to share data, to discuss alloying and thermal processing models, and to design needed experiments.

This project is a strategic study in which the influence of well controlled additions of alloying and microalloying elements to experimental gas-shielded cored welding wires will be investigated. Major aspects of the project include manufacture of cored consumables from high purity materials and assessment of details of the welds from these consumables with regard to mechanical properties, microstructure development and influence of non-metallic inclusions.

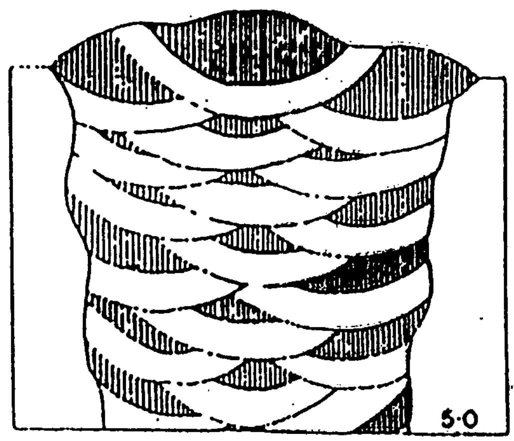
Results: Studies to date have included assessments of the influence of manganese, silicon, titanium, aluminium and boron on properties of welds from these wires. The combined influence of titanium and boron is currently under investigation. These results are being used to better understand the factors that control the mechanical properties of weld metal, particularly the low temperature impact properties. Analysis of results to date suggest that such impact properties are influenced by a number of factors including weld metal strength, number density of large non-metallic inclusions, proportion of acicular ferrite in the as-deposited metal and proportion of reheated weld metal.

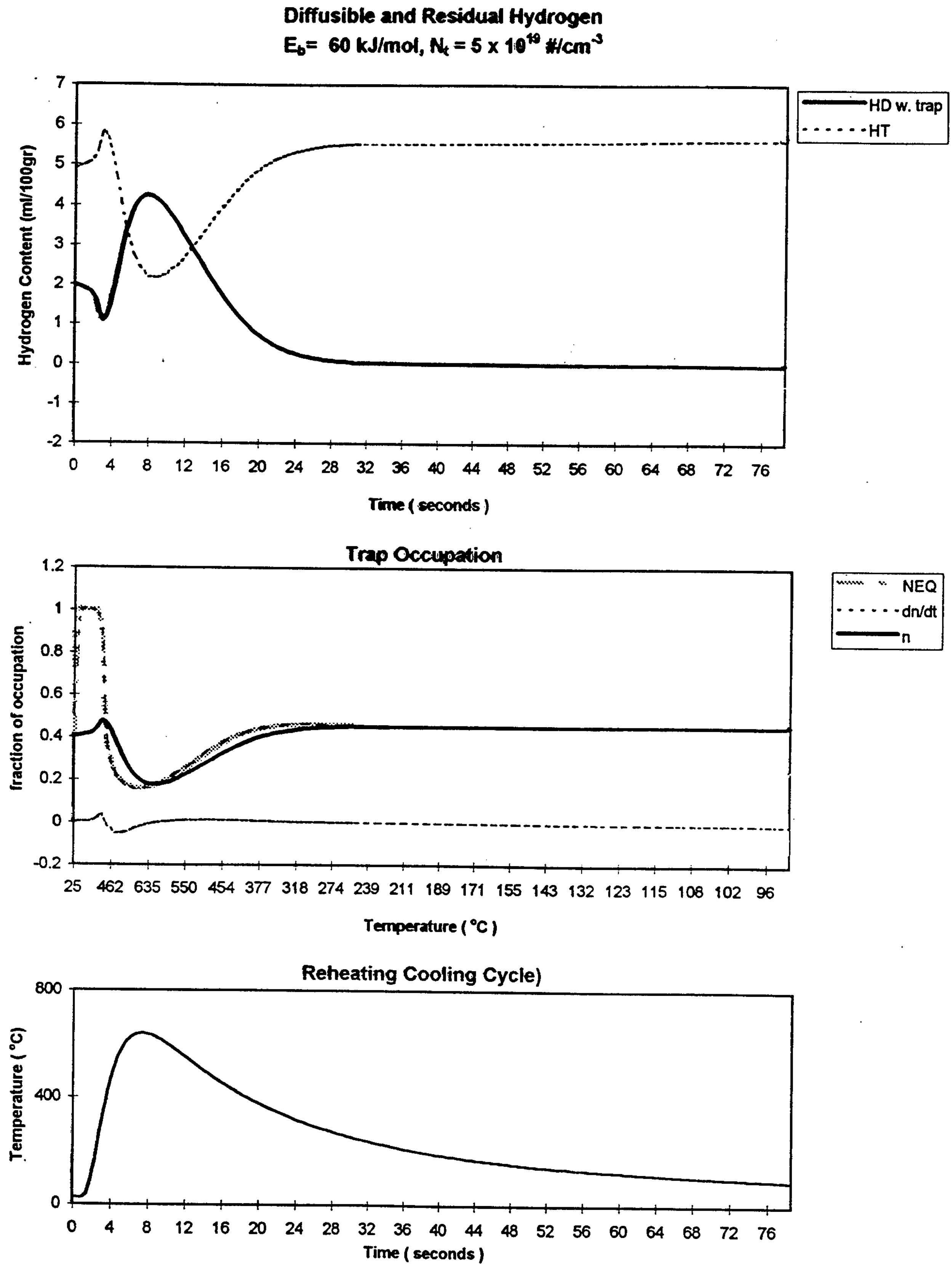
Plans: NA

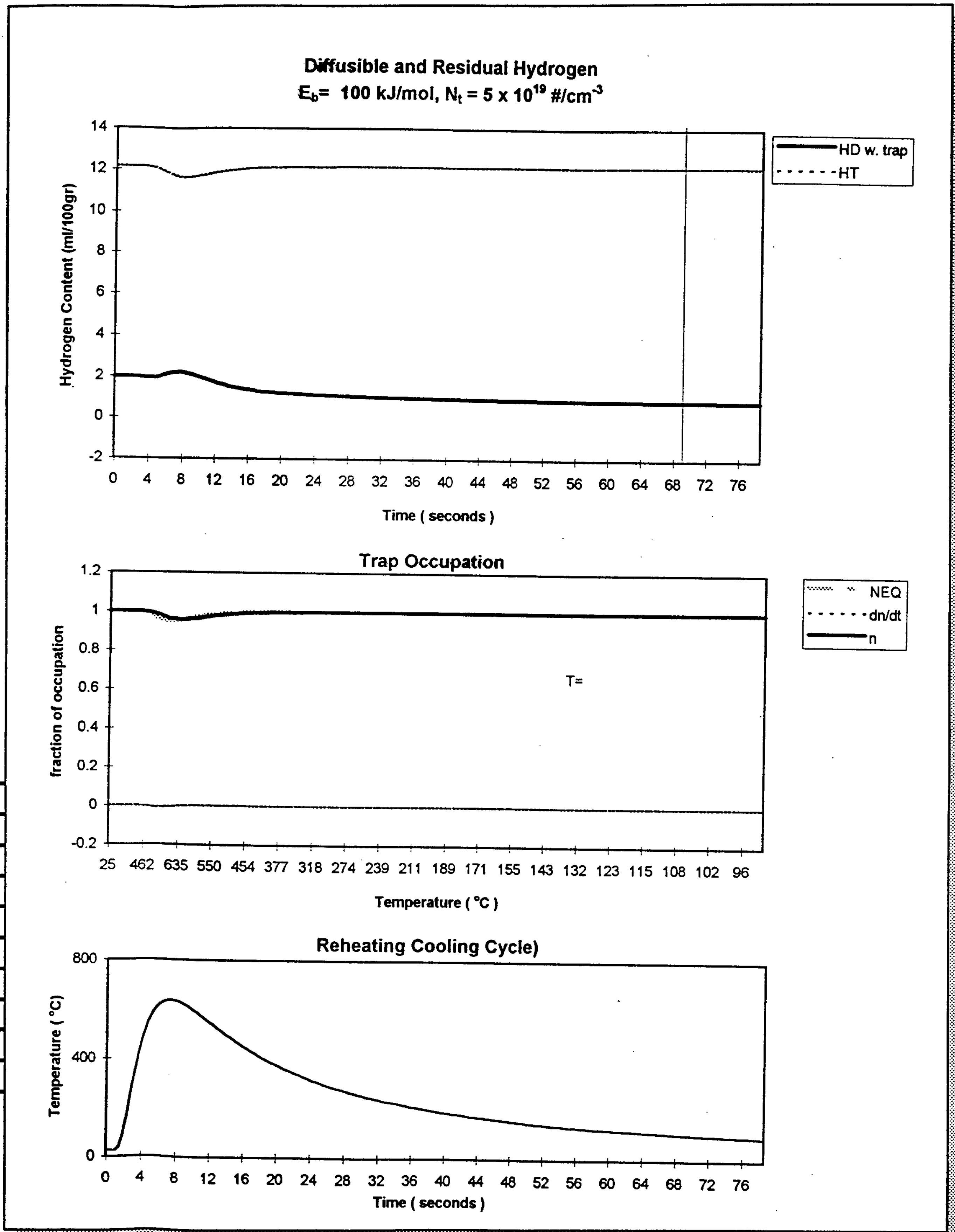
Status: in progress

Conclusion: 1999, Q4

Effect of Multiple Pass Behavior




Diffusible and Residual Hydrogen
E_b= 60 kJ/mol, N_t = 5 x 10^{19} #/cm^{-3}
Hydrogen Content (ml/100gr)
Time (seconds)
HD w. trap
HT
Trap Occupation
fraction of occupation
Temperature (°C)
NEQ
dn/dt
n
Reheating Cooling Cycle)
Temperature (°C)
Time (seconds)



Diffusible and Residual Hydrogen
E_b= 100 kJ/mol, $N_t = 5 \times 10^{19}$ #/cm^{-3}
Hydrogen Content (ml/100gr)
Time (seconds)
HD w. trap
HT
Trap Occupation
fraction of occupation
Temperature (°C)
NEQ
dn/dt
n
T=
Reheating Cooling Cycle)
Temperature (°C)
Time (seconds)

Task 3: Development of High Strength Steel Filler Metals

Activity 8: Use of Weld Metal Traps for Hydrogen Management

Organization: USA-CSM
USA-Lincoln Electric

Description: The use of weld metal hydrogen traps to reduce the available diffusible hydrogen content is being investigated. From literature reported and theoretically calculated binding energy values calculations have been made to assist in the selection of the most promising ferroadditions to be added to welding consumables.

Results: Selected ferroadditions of various transition metals and rare earths were made by CSM. Lincoln Electric Company has made metal filled cored wires with these additions at various content levels. A reproducible method to introduce specific hydrogen content into the weld metal was developed to allow for the evaluation of this concept of hydrogen management. An analytical arrangement and procedures to measure the hydrogen evolution rate as a function of weldment have been set up. Efforts have begun to measure the effectiveness of the Lincoln Electric produced experimental (with trapping additions) consumables. Preliminary results have shown drops in the diffusible hydrogen content due to trapping. Lincoln Electric is currently working on analyzing the recovery of ferroaddition to the wire. As soon as this recovery is known, another set of experimental wires can be made. Yttrium ferroadditions have demonstrated the most significant reduction in diffusible hydrogen content.

CSM has demonstrated three effective methods to improve welding consumables for hydrogen management. These methods are the selection of filler wire composition to produce an acceptable M_S temperature for the weld deposit relative to the base metal, the use of fluoride additions to the plasma, and the use of specific micro alloy additions to the consumable to achieve irreversible weld metal hydrogen traps. Some of these approaches are now being evaluated by U.S. welding consumable companies.

Plans: NA

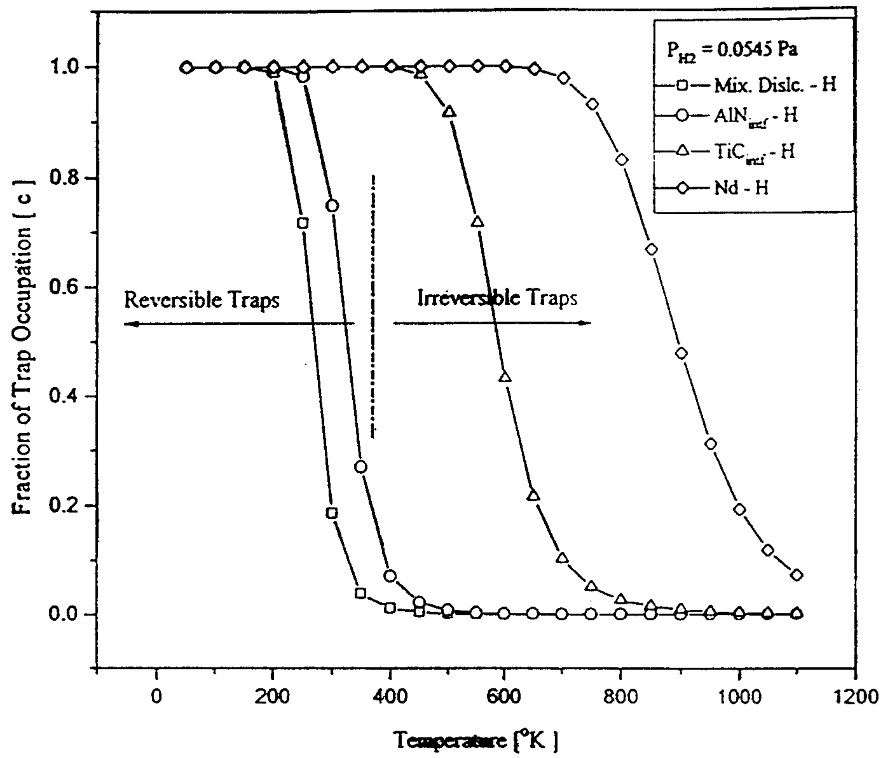
Status: in progress

Completion: 1999, Q3

Hydrogen Trapping

Trap occupation by hydrogen as predicted by Fermi-Dirac distribution

Fraction of trap occupation as a function of temperature for various type of traps at hydrogen partial pressure $P_{H2} = 0.0545$ Pa



1. Open system: $\frac{1}{2}H_2 = \underline{H}$, at H_2 pressure = P

$$c_{\underline{H}} = 0.00185\sqrt{P}\exp\left(\frac{28600}{RT}\right), \qquad [P : atm]$$

[T : °K]

2. Trapping : $\underline{H} + X = H_x$

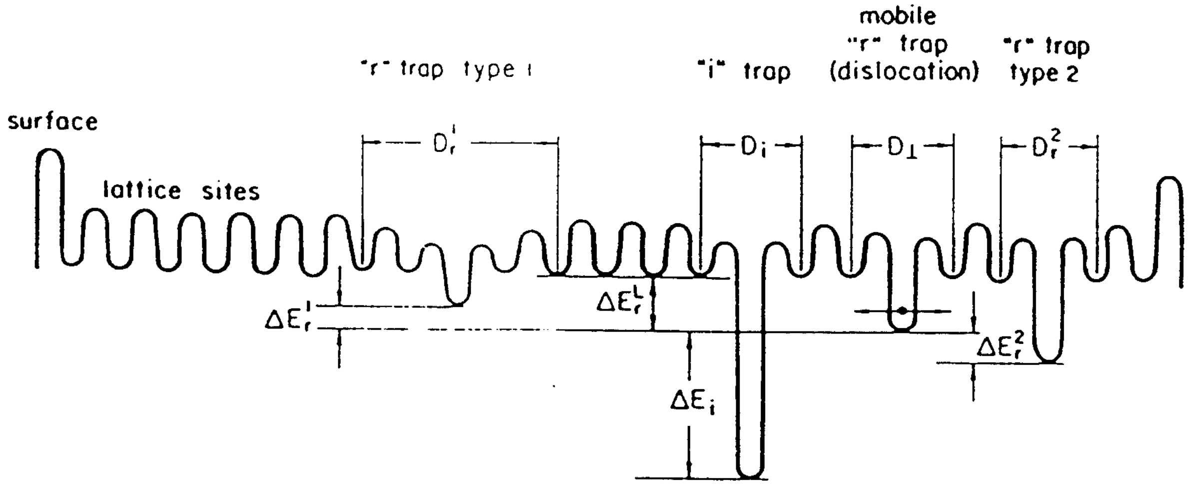
$$\frac{c}{1-c} = \frac{c_{\underline{H}}}{1-c_{\underline{H}}}\exp\left(\frac{E_b}{RT}\right) \cong c_{\underline{H}}\exp\left(\frac{E_b}{RT}\right), \qquad [E_b : kJ/mol]$$

where E_b = Trap - H binding energy

1+2. $$\frac{c}{1-c} = 0.00185\sqrt{P}\exp\left(\frac{E_b - 28600}{RT}\right)$$

Hydrogen Trapping

Trap Site Classification



Schematic of general traps, trapping energies, and the influence diameters.

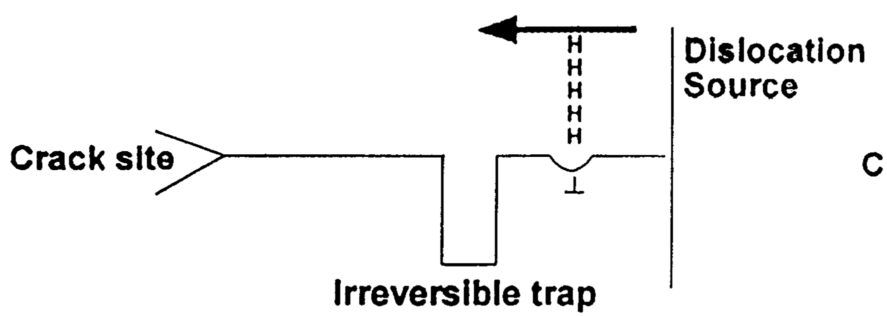
Strength of Various Traps in Ferrous Alloys

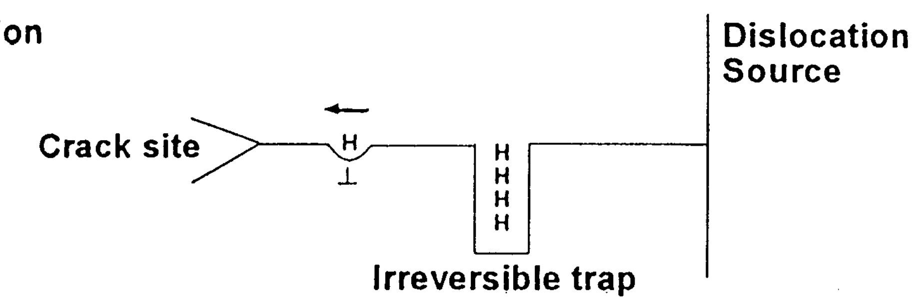
Schematic Description	Nature of the Trap	Character of the Trap at Room Temperature	E (Trap-H) (eV)
Lattice sites	Lattice site	Very Reversible diffusion site	0.08
"r" trap - type 1	Titanium substitutional atom	Reversible	0.27
"i" trap	Titanium Carbide Particle (TiC)	Irreversible	0.98 0.8-0.98
mobile "r" trap (dislocation)	Dislocation	Reversible	0.25
"r" trap - type 2	Grain boundary	Reversible	0.27 0.55-0.61

Ref.: Pressouyre & Bernstein

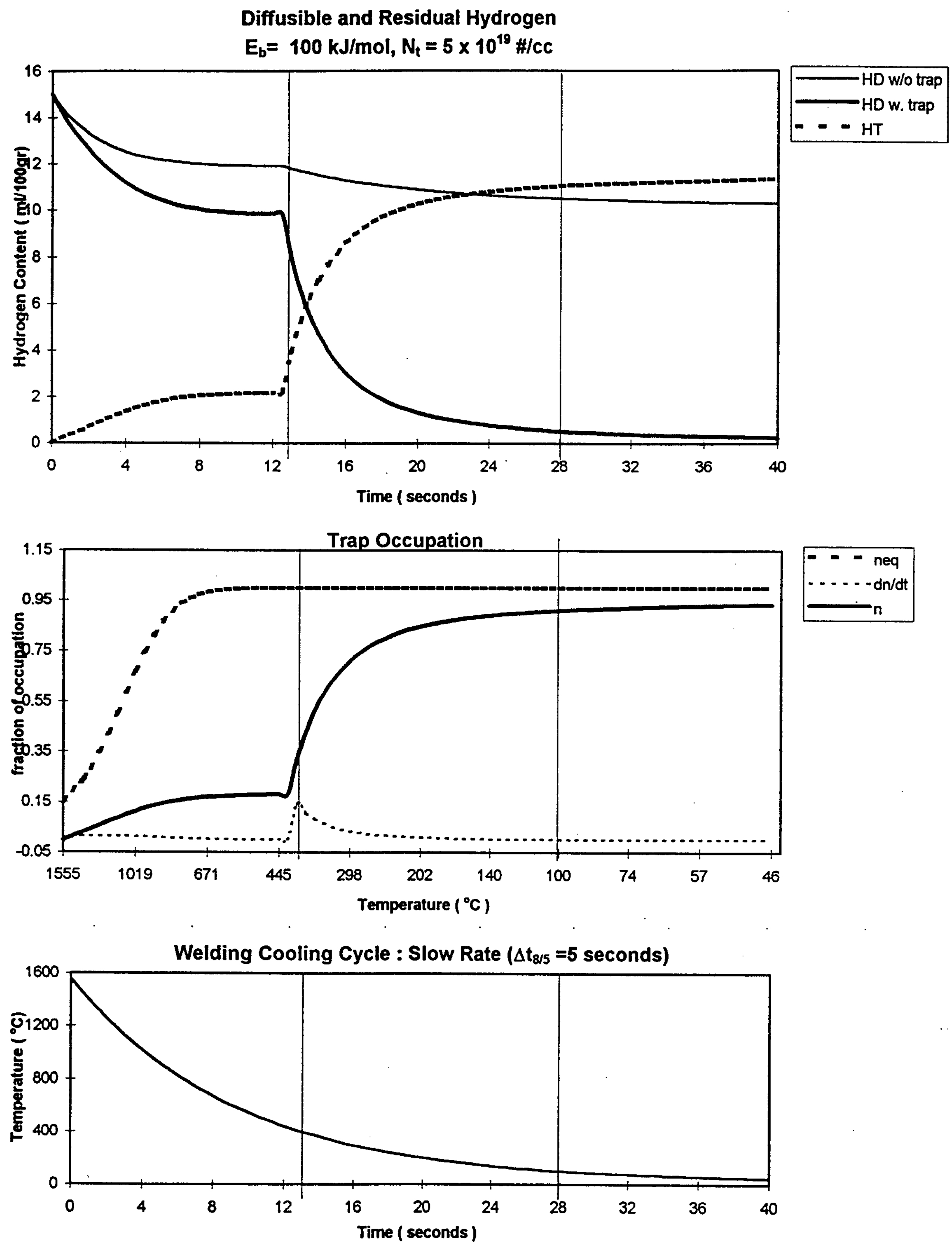
Hydrogen Trapping

The role irreversible trap sites in preventing hydrogen induced cracking





- **Before a dislocation pass through an irreversible trap site**
  - High dislocation velocity
  - High potential for hydrogen accumulation at the crack tip
- **After a dislocation pass through an irreversible trap site**
  - Low dislocation velocity
  - Low potential for hydrogen accumulation at the crack tip

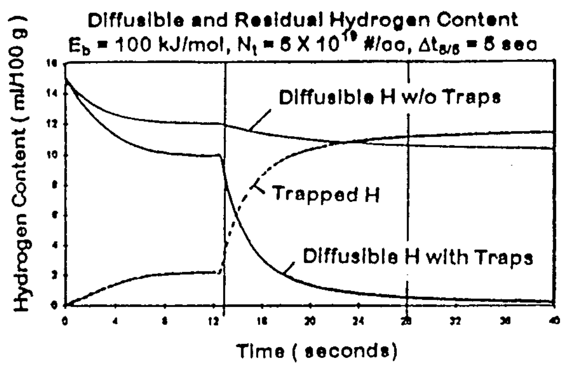


Diffusible and Residual Hydrogen
E_b= 100 kJ/mol, $N_t = 5 \times 10^{19}$ #/cc
Hydrogen Content (ml/100gr)
Time (seconds)
HD w/o trap
HD w. trap
HT
Trap Occupation
fraction of occupation
Temperature (°C)
neq
dn/dt
n
Welding Cooling Cycle : Slow Rate ($\Delta t_{8/5}$ =5 seconds)
Temperature (°C)
Time (seconds)

High Strength Steel Welding Research

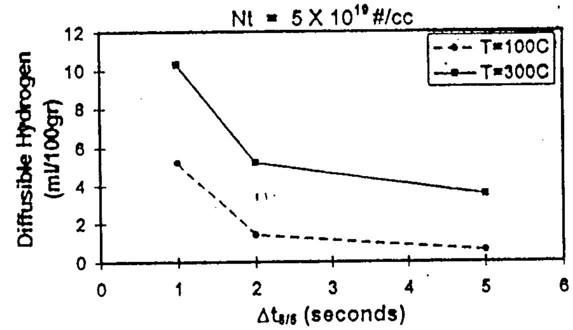
Hydrogen Trapping in Ferrous Weldments

Hydrogen Trapping During Welding Cooling Cycle Results in Lower Diffusible Hydrogen Content



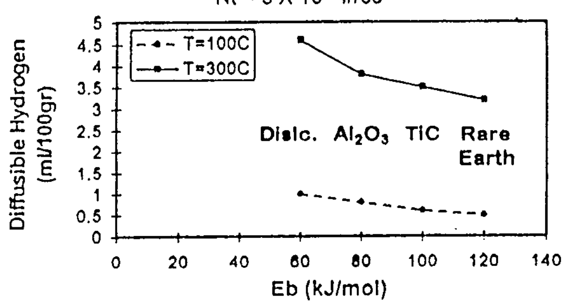
Effect of Cooling Rate

Initial Diffusible Hydrogen Content = 15 ml/100 gr
Ms = 400C
Eb = 100 kJ/mol
Nt = 5 X 10^{19} #/cc

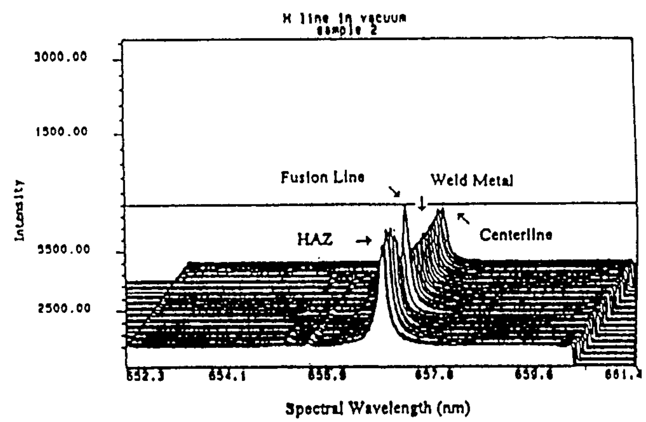


Effect of Trap Binding Energy

Initial Diffusible Hydrogen Content = 15 ml/100 gr
Ms = 400C
$\Delta t_{8/5}$ = 5 seconds
Nt = 5 X 10^{19} #/cc



Localized Hydrogen Accumulation in Weldment Without the Effect of Hydrogen Trapping



Hydrogen-Trap Binding Energy Assessment

Kissinger's equation :

$$\frac{\partial \ln\left(\phi / T_m^2\right)}{\partial\left(1 / T_m\right)} = -\frac{E_a}{R}$$

ϕ = heating rate (K/min)

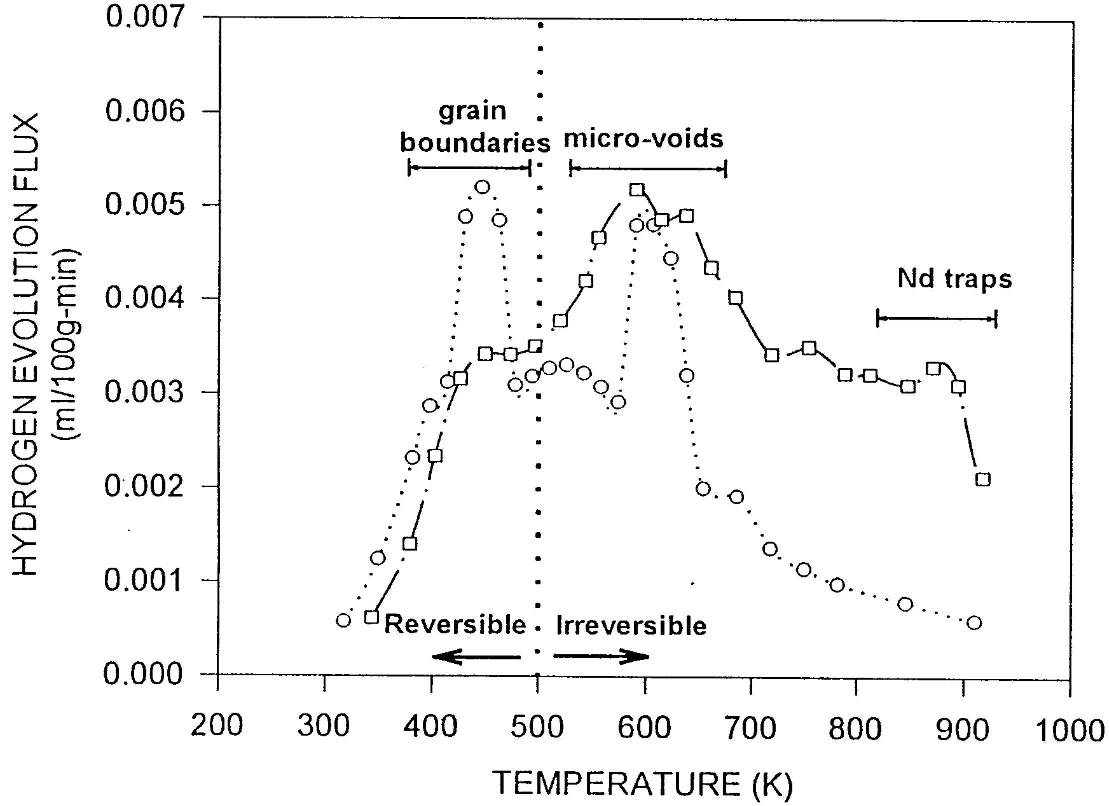
T_m = hydrogen evolution peak temperature

R = universal gas constant

E_a = activation energy for hydrogen release from a trap site

= $E_B + E_L$

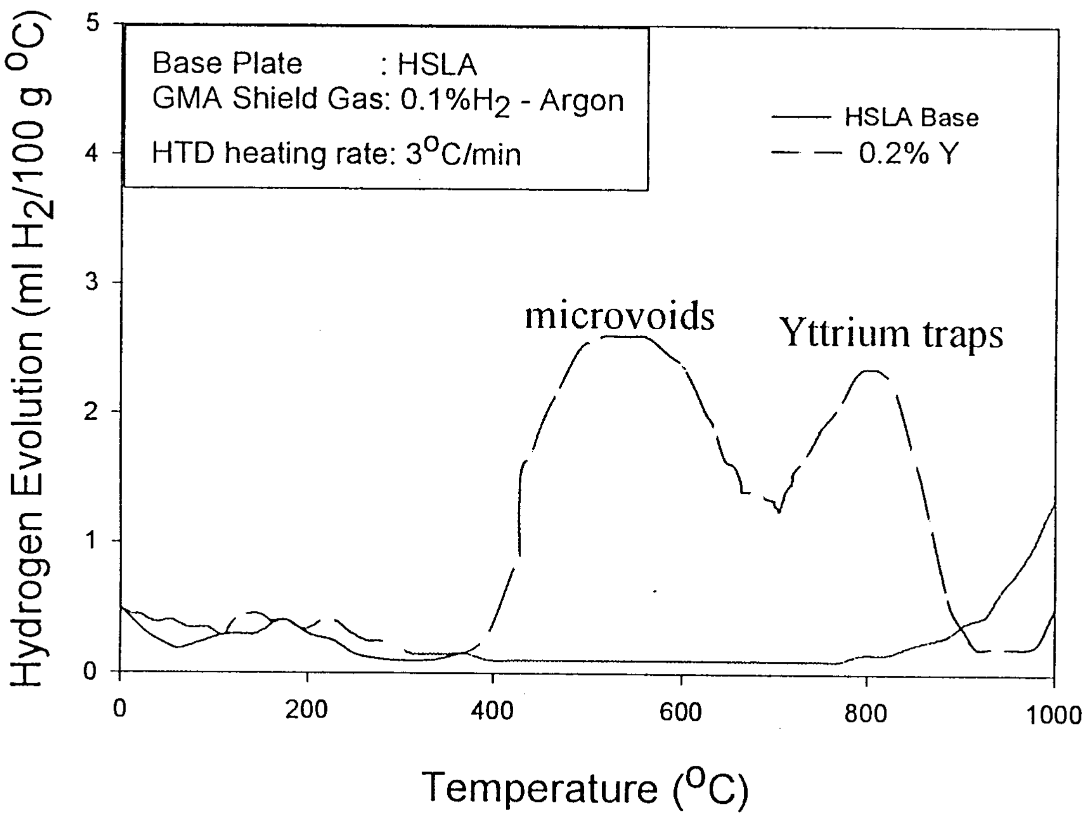
Thermal Desorption Analysis Curve



- Neodymium traps are irreversible.
- Neodymium containing weld metal has higher trapped hydrogen content than that without trap.
- Verify that the reduction of diffusible hydrogen is due to hydrogen trapping.

Experimental

Thermal Desorption Analysis Curve

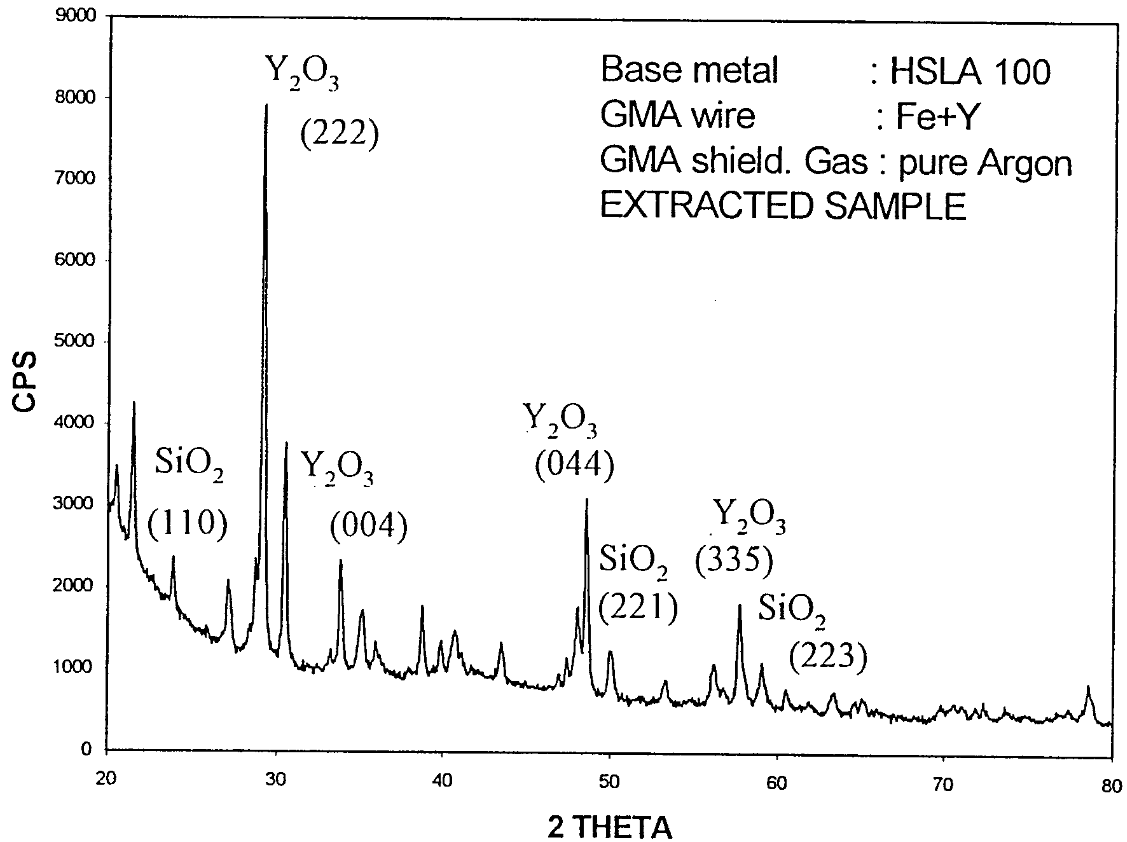


- Yttrium traps are irreversible.
- Yttrium containing weld metal has higher trapped hydrogen content than that without trap.
- Verify that the reduction of diffusible hydrogen is due to hydrogen trapping.

Experimental

Identification of Trapping Inclusions

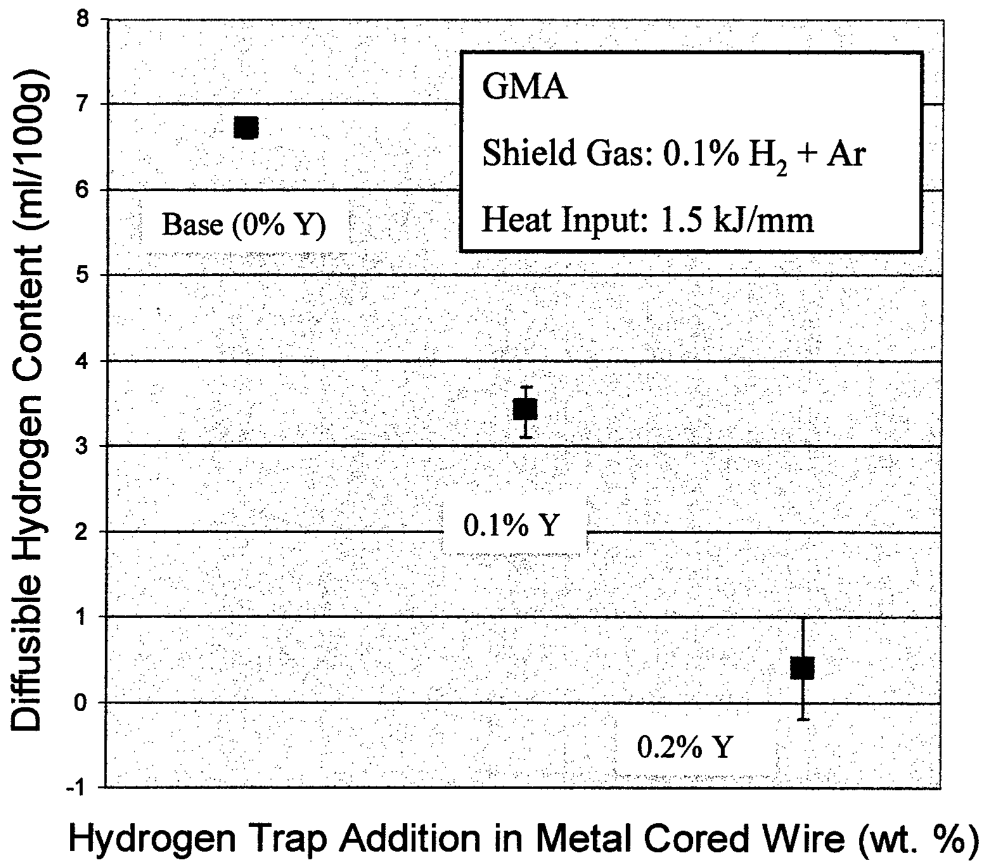
X-RAY DIFFRACTION



* Extraction of inclusion from steel matrix by digestion in bromine and methanol solution.

* X-Ray diffraction of inclusion powders collected from extraction process.

Diffusible Hydrogen Reduction



HSLA Weld

* The reduction of diffusible hydrogen weld metal content is reduced from 6.7 ml H_2/100g to 0.5 ml H_2/100g by adding 0.2 wt. % Y (in the form of Fe_2Y) in the metal cored wire.

Task 3: Development of High Strength Steel Filler Metals

Activity 9: Analytical Methods to Evaluate Weld Hydrogen Content and Hydrogen Distribution

Organization: USA-CSM
USA-SUNY-Albany
USA-Lincoln Electric

Description: The hydrogen distribution in a weld becomes significantly more important as the acceptable diffusible hydrogen contents decrease. With the ever increasing use of steels of higher strength analytical techniques need to be developed to measure hydrogen distribution across the weld. These localized hydrogen contents are most likely the cause in the spread of the correlation between the measured diffusible hydrogen contents and cracking tendencies. A number of methods are being explored to measure hydrogen distributions. These methods included laser induced breakdown spectroscopy (LIBS), hydrogen exposure to silver bromide coatings, laser ablated gas chromatography, hydrogen changing the electrical conductivity of W_3O coatings, and MeV ion Beam Analysis.

CSM has developed and demonstrated the use of optical and electronic techniques to measure diffusible hydrogen and weld hydrogen distribution in weldments.

Results: Preliminary results have successfully measured hydrogen distributions. The W_3O oxide coating conductivity concept shows promise of attaching adhesive electrical device to read diffusible hydrogen directly from welded components.

A diffusible hydrogen sensor for welded steel is currently under development at the Colorado School of Mines and the National Renewable Energy Laboratory. Preliminary experiments have demonstrated that the sensor can detect hydrogen directly from a weld deposit and that it possesses high sensitivity. The sensor is designed to sample from actual welded structures as opposed to sample coupons; results from the sensor can be obtained in minutes instead of hours. This device provides the potential for alleviating the cost and time expenditure associated with standard diffusible hydrogen testing. Future work needs to project laboratory successes in the design of advanced hydrogen sensors for technological transfer to high strength steel fabricators.

Plans: Efforts will be made to develop an analytical practice to supplement the information presently reported by the costly and time consuming diffusible hydrogen measurements.

Status: in progress

Completion: 1999, Q3

Thermodynamic Properties

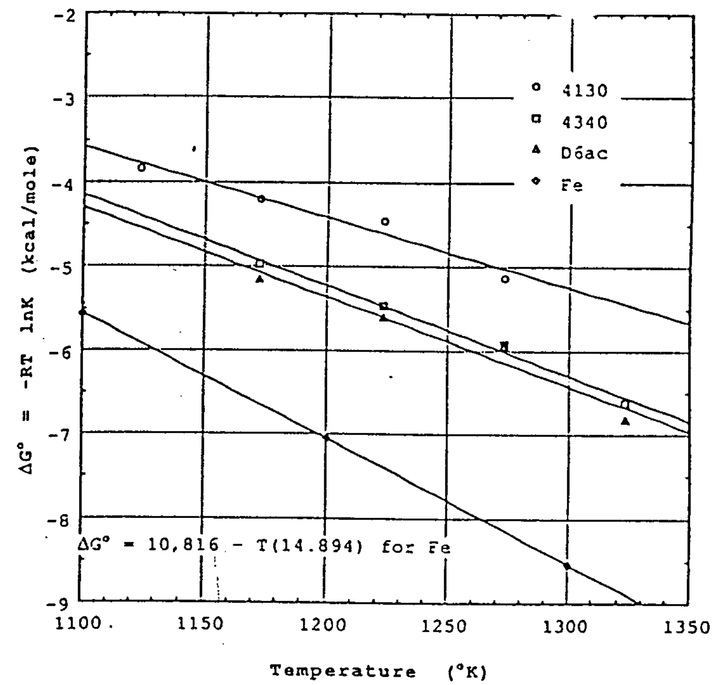
AISI 4130: $\Delta G^o = 5573.7 - 8.3320\ T$

AISI 4340: $\Delta G^o = 7708.9 - 10.784\ T$

Laddish D-6ac: $\Delta G^o = 7424.4 - 10.662\ T$

Pure Iron: $\Delta G^o = 10816 - 14.89\ T$

Solubility increases with increased availability of sites, indicated by higher, ΔS^o



Ingress Diffusion

Lattice diffusivity, $D = D_o \exp^{-Q/RT}$.

Activation energy, Q, and pre-exponential factor, D_o in α- iron: 10.7 kcal/mole and 0.0047 cm^2/sec.

Lattice diffusivity determined by the fractional saturation method. The appropriate hydrogen concentrations at various times, t, used to determine the diffusivity at different temperatures using Fick's 1st Law.

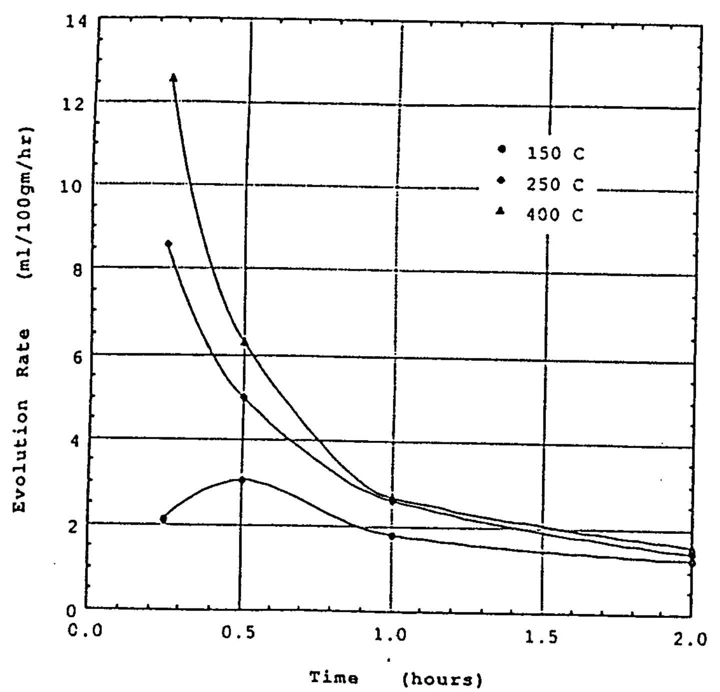
ln D vs. *1/T* plot gives pre-exponential factor and the activation energy.

$D_o = 0.551\ cm^2/s$ and $Q = 22$ kcal/mole.

Dissociation of the hydrogen molecule prior to absorption is the controlling step.

$$\ln D = -10734/T - 0.87128$$ *average diffusivity*

Egress Diffusion



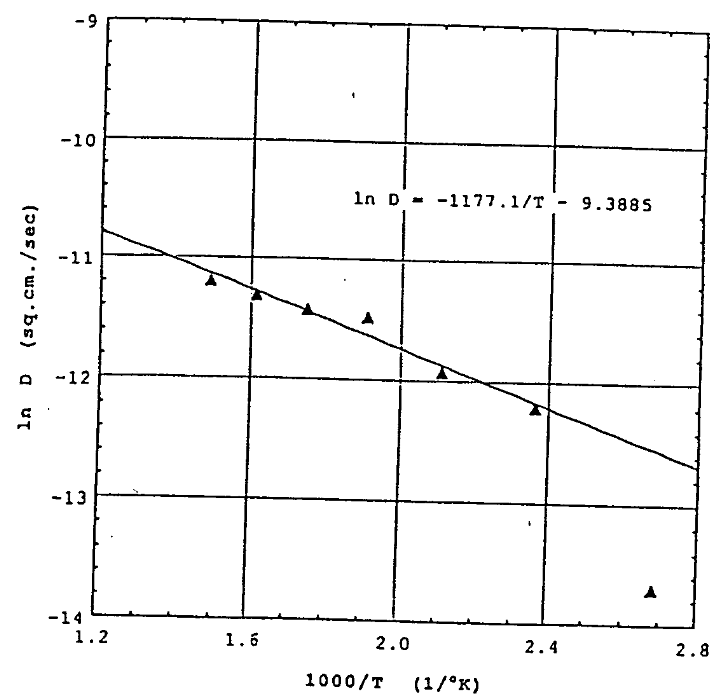


Figure 8: Diffusivity of hydrogen for AISI 4340 steel after sixty minutes of desorption.

Hydrogen Management in Steel Welds: Techniques to Measure Hydrogen Distribution

Hydrogen distribution is a serious issue regarding the integrity of higher strength steel welds

OBJECTIVE :

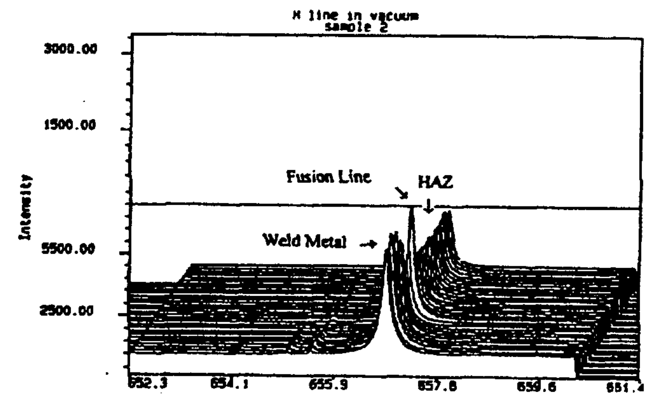
The development of advanced methods for measurement of hydrogen distributions.

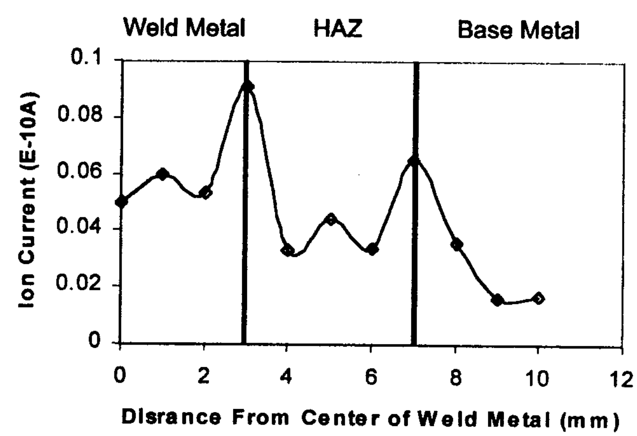
APPROACH :

The use of laser ablation coupled with various detection techniques including emission spectroscopy and mass spectrometry.

RESULTS :

Numerous potential techniques were evaluated. Hydrogen distribution profiles were generated using Laser Induced Breakdown Spectroscopy (LIBS) and Laser Ablation/Mass Spectroscopy (LA/MS). LA/MS was selected to develop an analytical tool for hydrogen distribution measurement. The LA/MS technique and associated equipment is being evaluated and optimized. A patent disclosure is likely.





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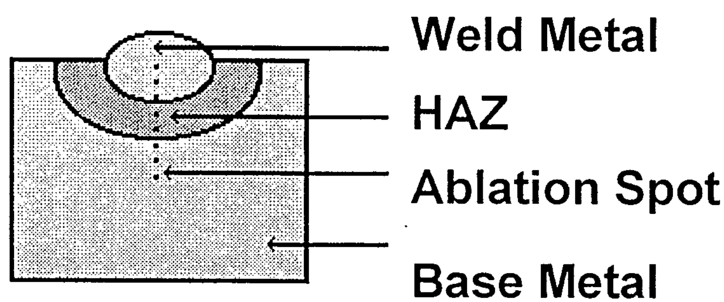
Methods for the Determination of Total Hydrogen Distribution

Laser Ablation Methods:

* Allow analysis of total hydrogen concentration by vaporization of surface sample material.

1. Laser Induced Breakdown Spectroscopy (LIBS)
2. Laser Ablation/Gas Chromatography (LA/GC)
3. Laser Ablation/Mass Spectrometry (LA/MS)



LIBS Data

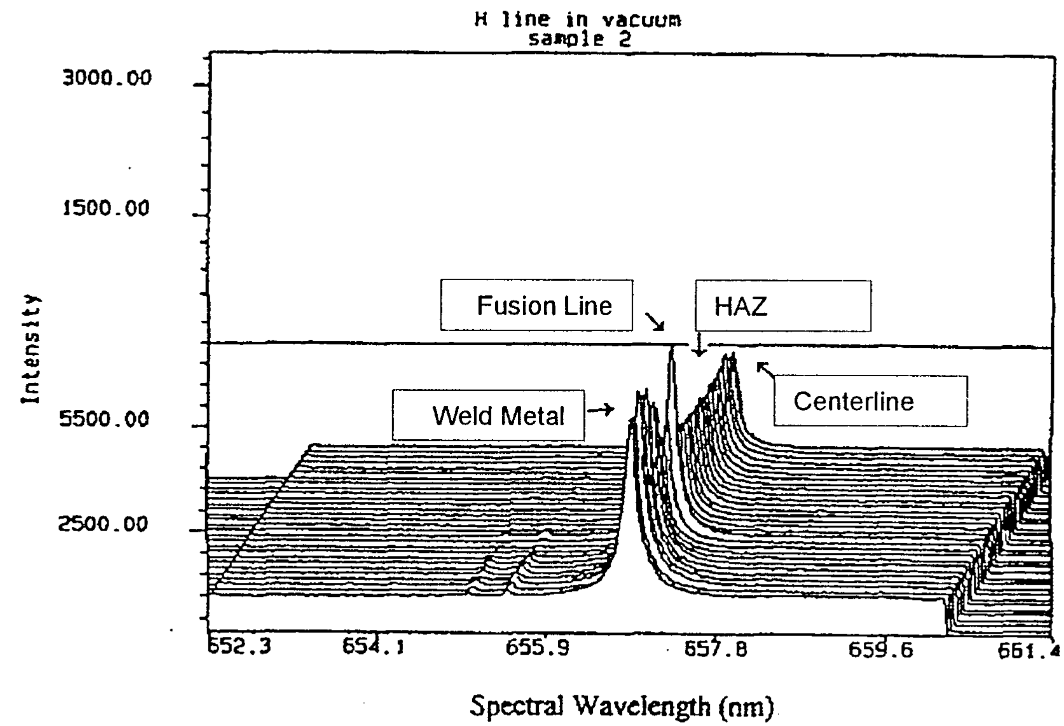


Figure 1. Non-uniform distribution of hydrogen across the center line of a weldment. Intensities of the hydrogen spectral emission are proportional to the hydrogen concentration.

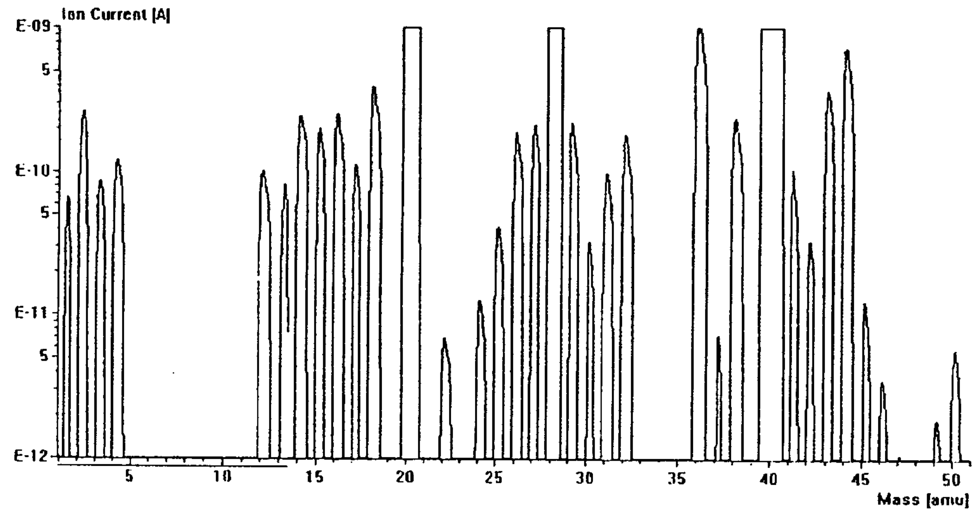
Dave Smith (CSM) & David Cremers (LANL)

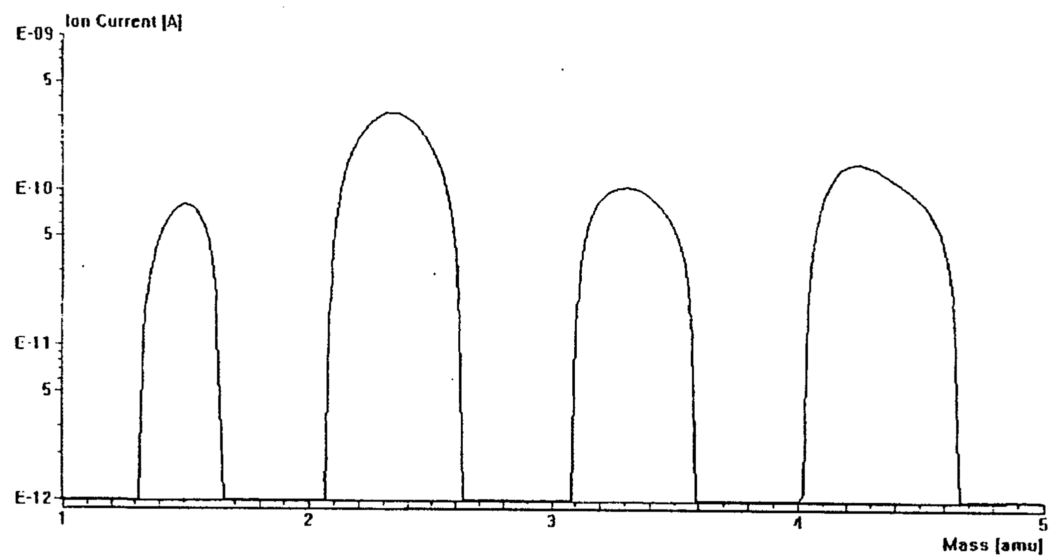
LA/GC Data

Sample	Shielding Gas (% Hydrogen)	Area	Peak area	Concentration (ppm)
1	1.0	Weld	448934	3.6
1	1.0	HAZ	234860	2.1
1	1.0	Base	218397	2.0
2	1.0	Weld	503170	3.9
2	1.0	HAZ	412257	3.3
2	1.0	Base	467646	3.7

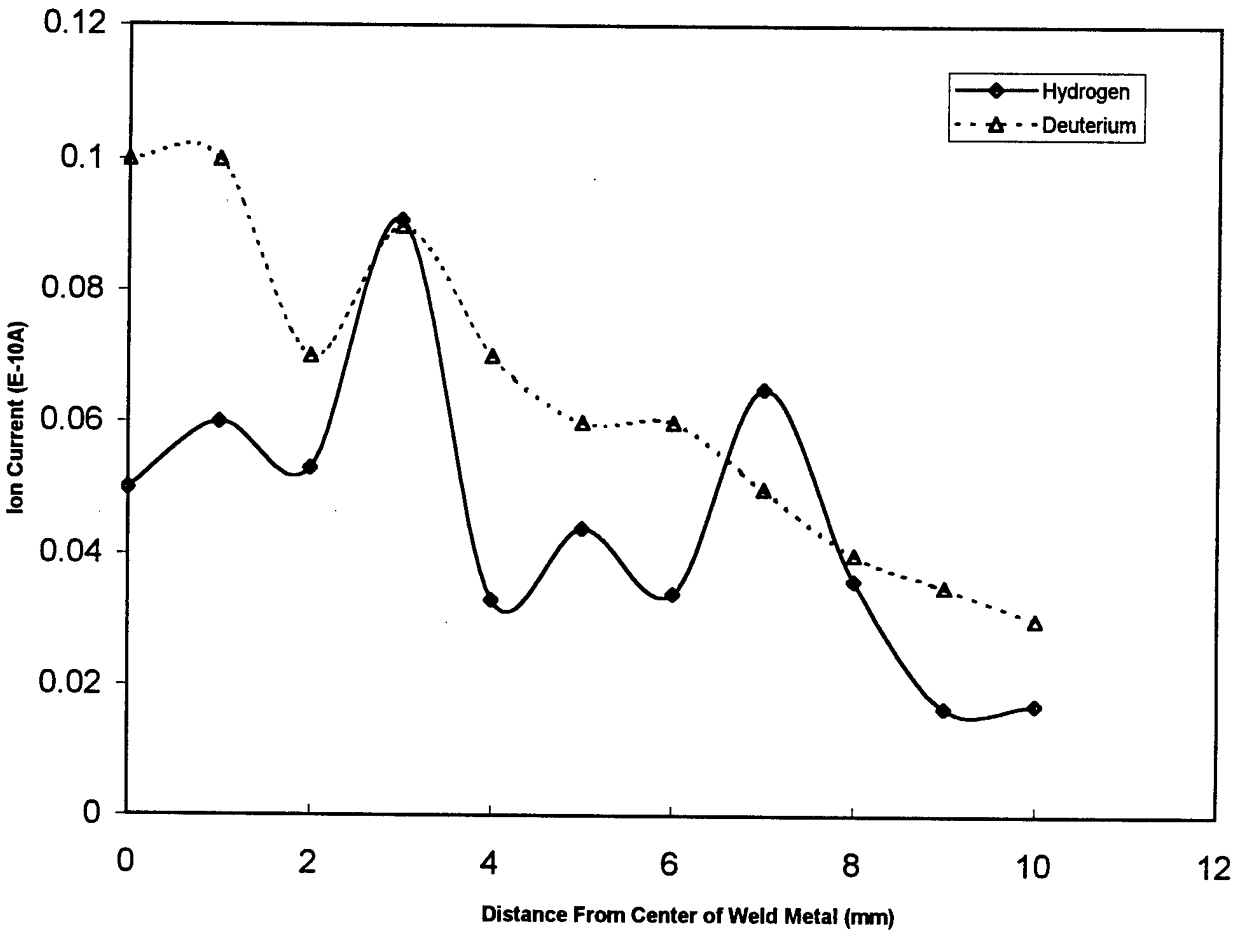
Dave Smith & Tom Wildeman (CSM)

LA/MS Data





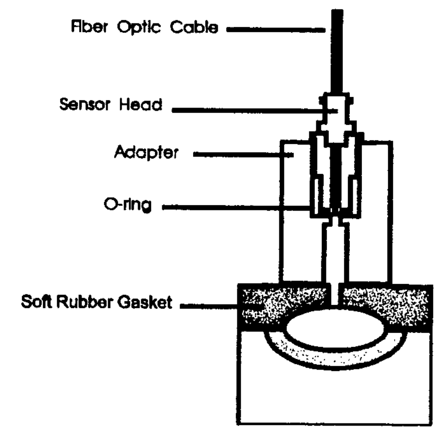
Dave Smith (CSM) & Gary Landis (USGS)



LA/MS Distribution Profiles For GMA Welded HSLA 100 Steel (Mild Steel Wire; 0.5% Deuterium/Argon Shielding Gas)

Hydrogen Management in Steel Welds: Optoelectronic Sensor For Diffusible Hydrogen

Higher strength steel welds are subject to Hydrogen Assisted Cracking. The existing analytical practice to measure diffusible hydrogen takes from 24-72 hours and is performed on laboratory specimens.



OBJECTIVE :

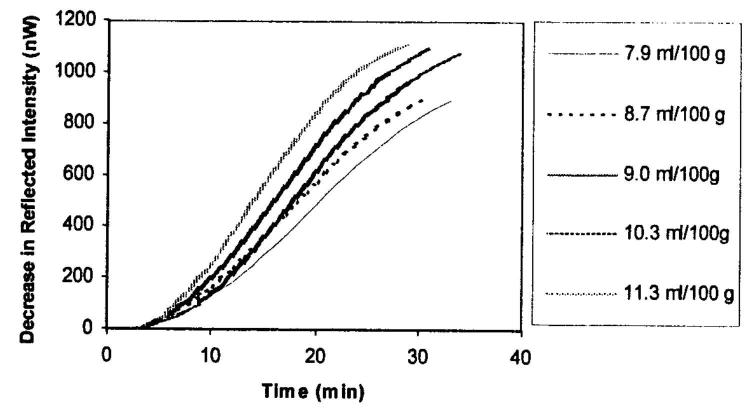
The development of new techniques for diffusible hydrogen measurement based on the optoelectronic properties of transition metal oxide films.

APPROACH :

The use of diffusion analysis to predict initial concentrations of welded steel samples.

RESULTS :

The sensor measures hydrogen flux directly from the weld deposit and is calibrated in ml/100g weld metal. The sensor is extremely sensitive to hydrogen and generates results in minutes. It can also be adapted to measure diffusible hydrogen associated with gun barrels.
(patent pending)



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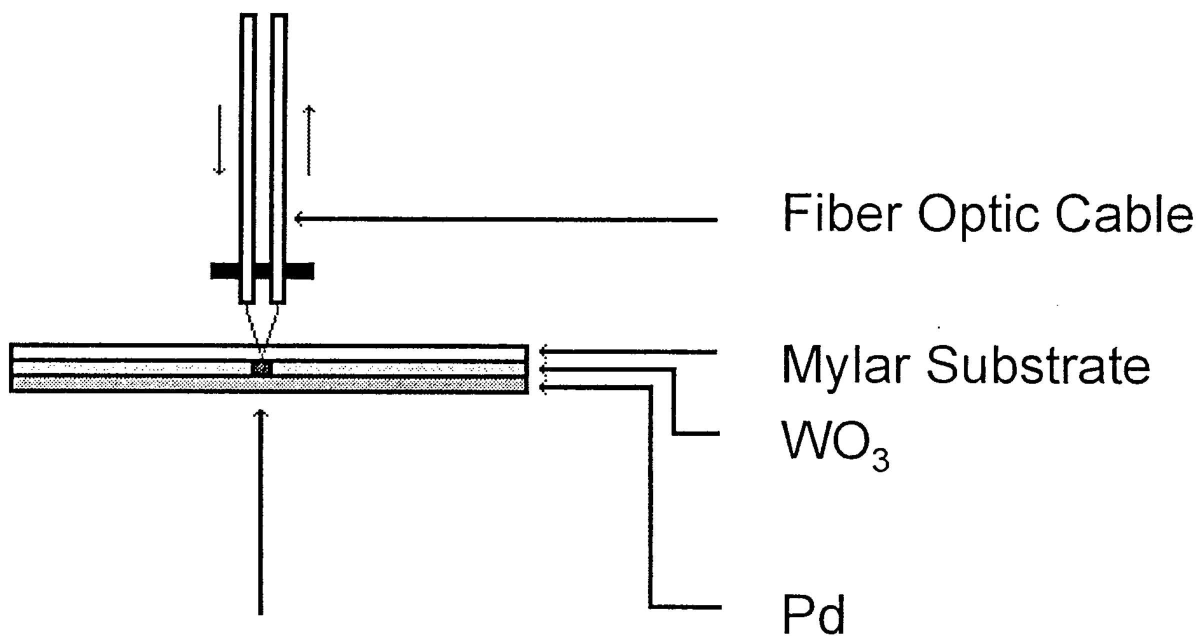
Methods for the Determination of Diffusible Hydrogen Distribution

WO_3 Based Hydrogen Sensor:

- The sensor consists of a thin film of tungsten (VI) oxide coated with an additional film of palladium catalyst. Evolved hydrogen from a steel sample is dissociated by the Pd and reacts with WO_3 to form a blue colored complex. The color change is measured by reflectance spectroscopy using a fiber optic cable.

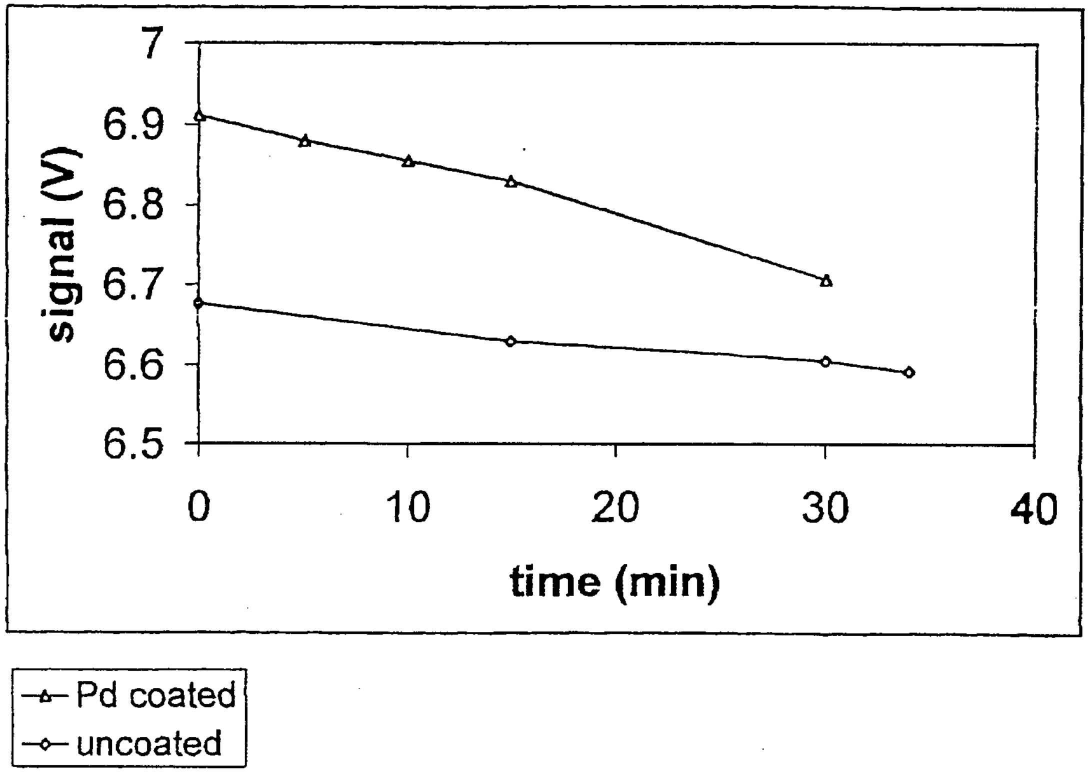
- Allow diffusible hydrogen analysis by detecting evolved gas from a welded sample.

Design for WO_3 Based Hydrogen Sensor



David Benson (NREL) & Dave Smith (CSM)

WO_3 Thin Film Hydrogen Sensor



* Hydrogen Flux Measurements from Pd Coated and Uncoated HSLA Steel Using WO3 Based Fiber Optic Sensor

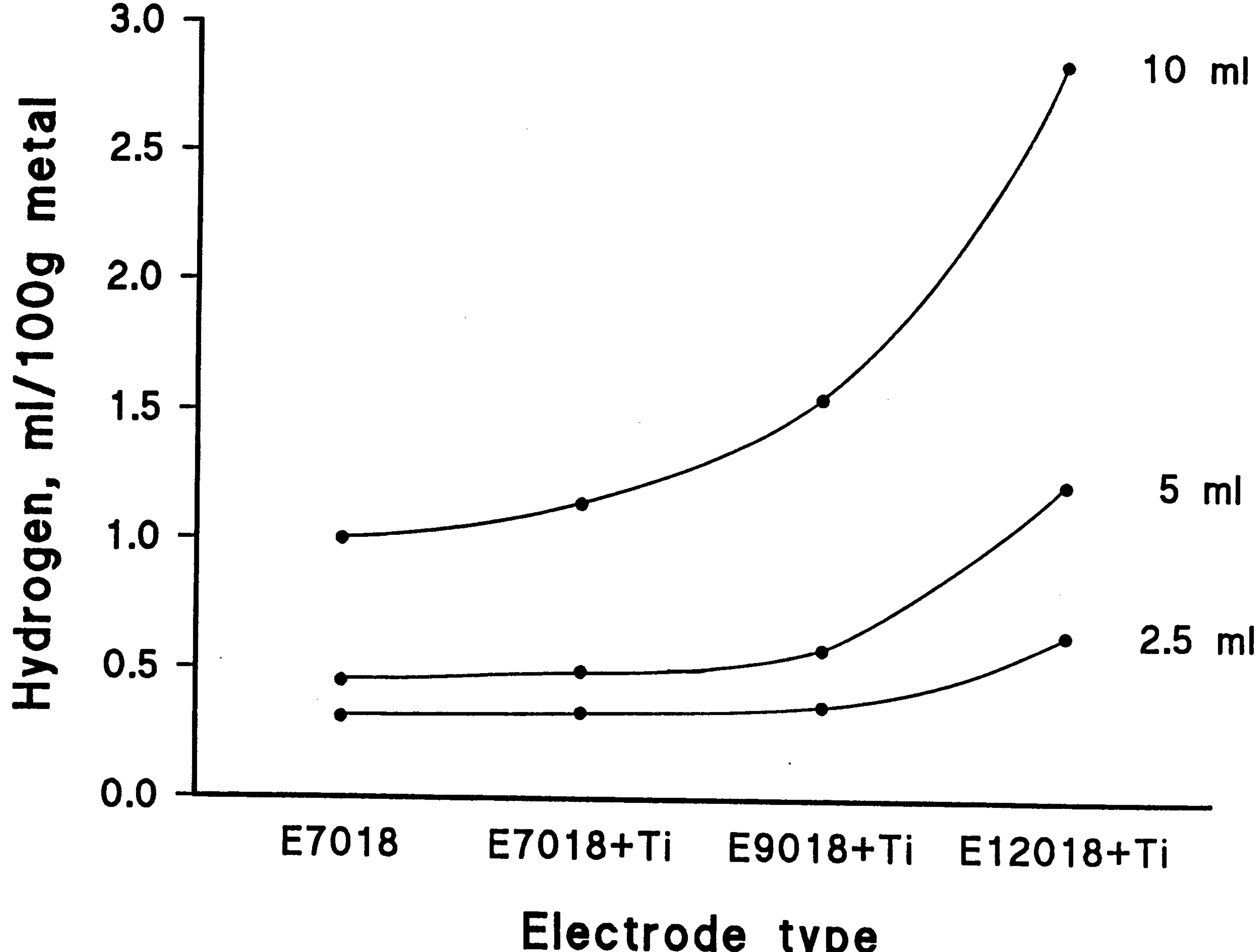
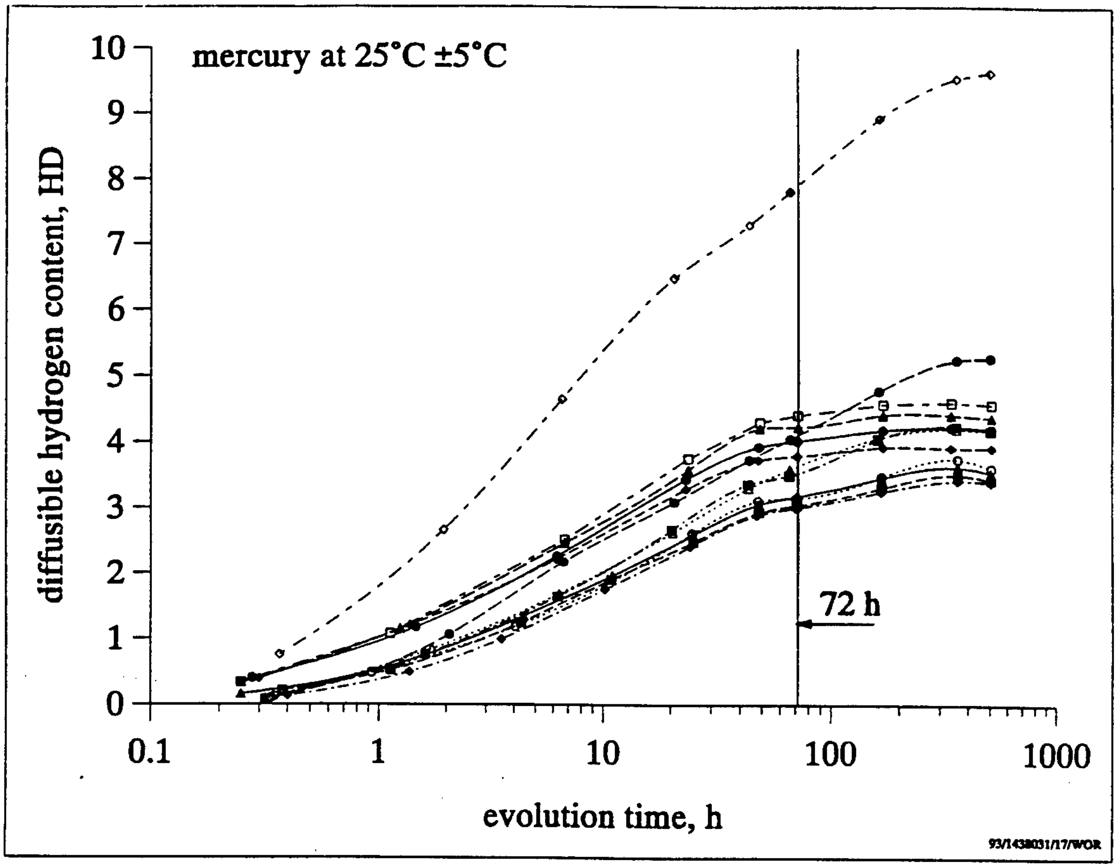


Figure 1: Diffusible hydrogen in multipass welds, 3 days at 150°C



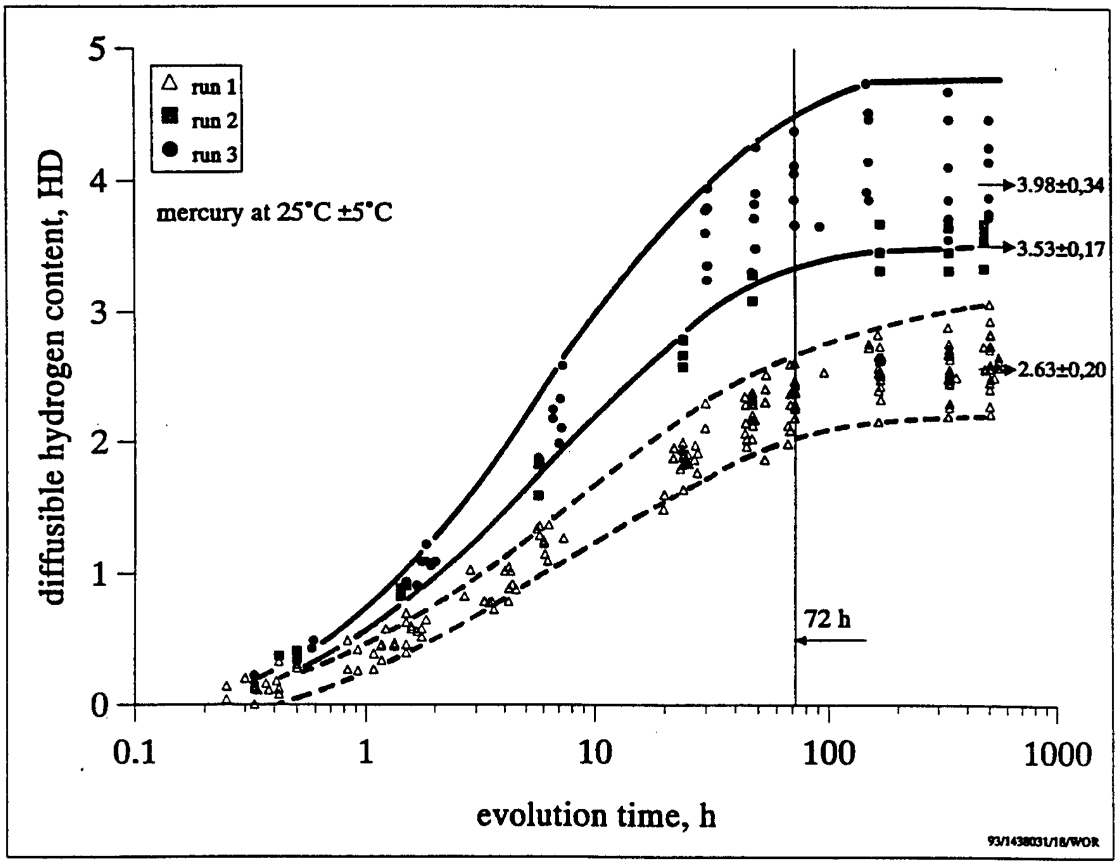


Figure 1 Hydrogen levels as a function of the evolution time in mercury at 25°C ±5°C

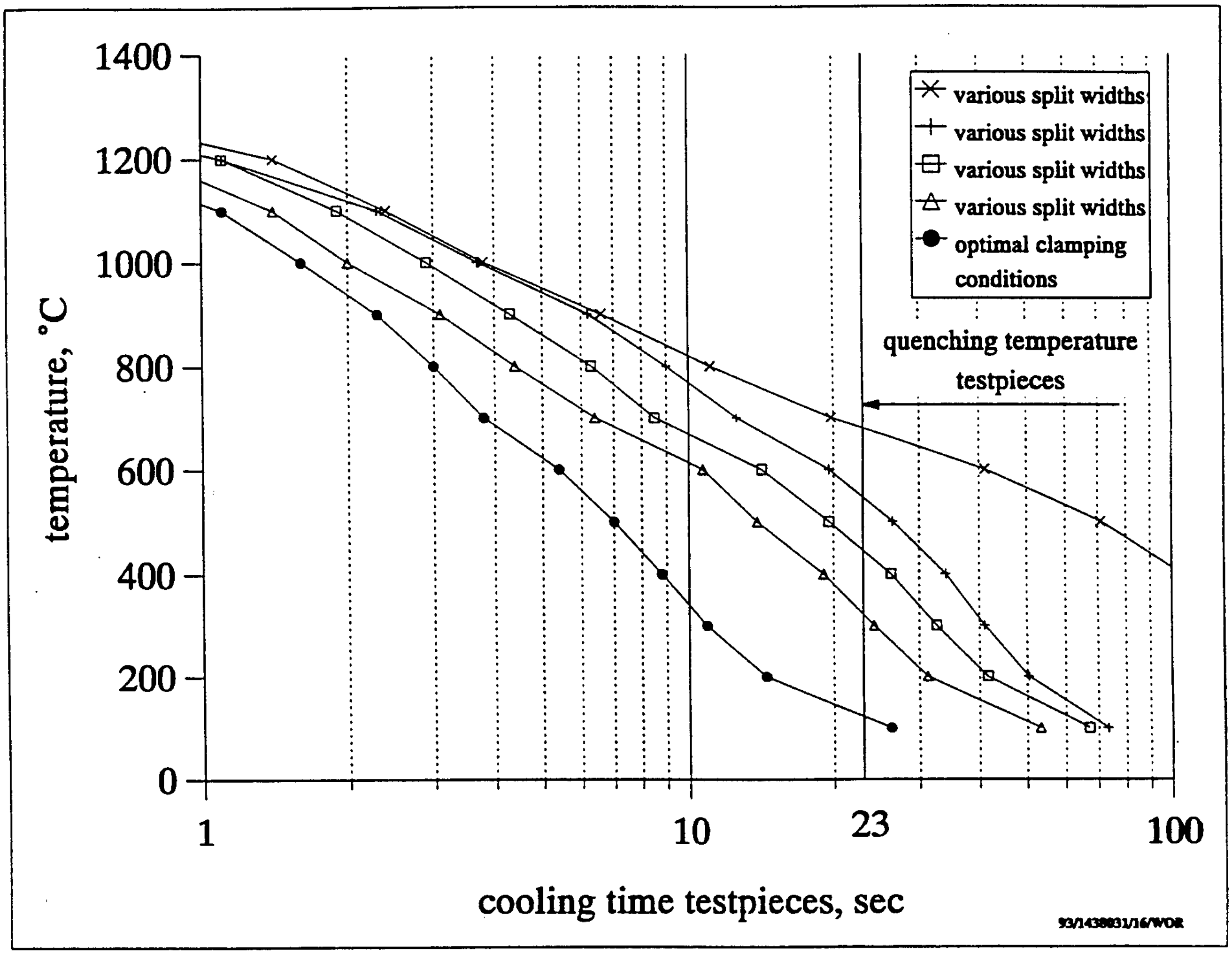


Figure 2 The influence of the clamping conditions on the cooling rate and quenching temperature

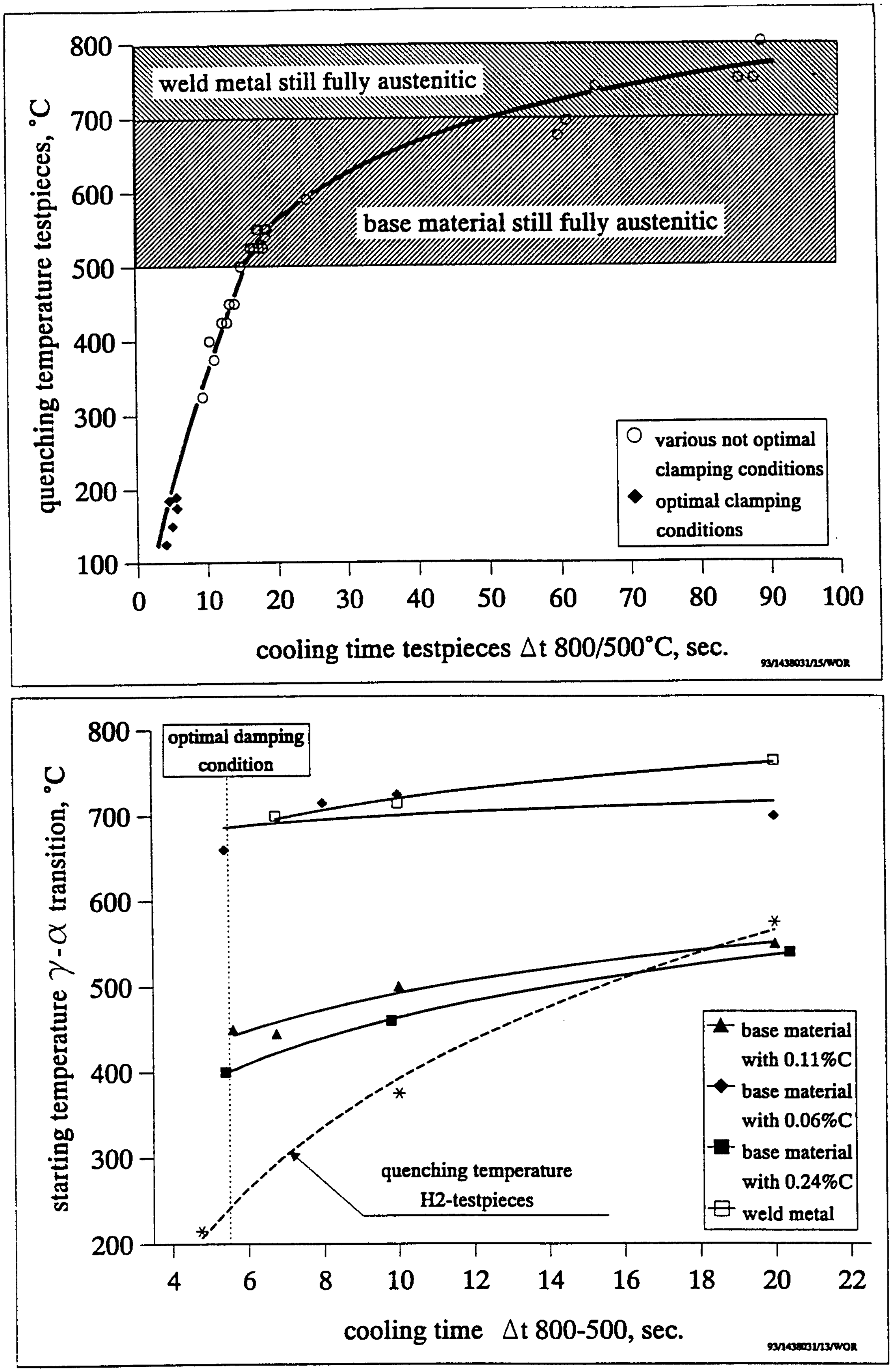


Figure 3 Austenite/ferrite transformation temperatures for heat affected zone material and E7018 weld metal

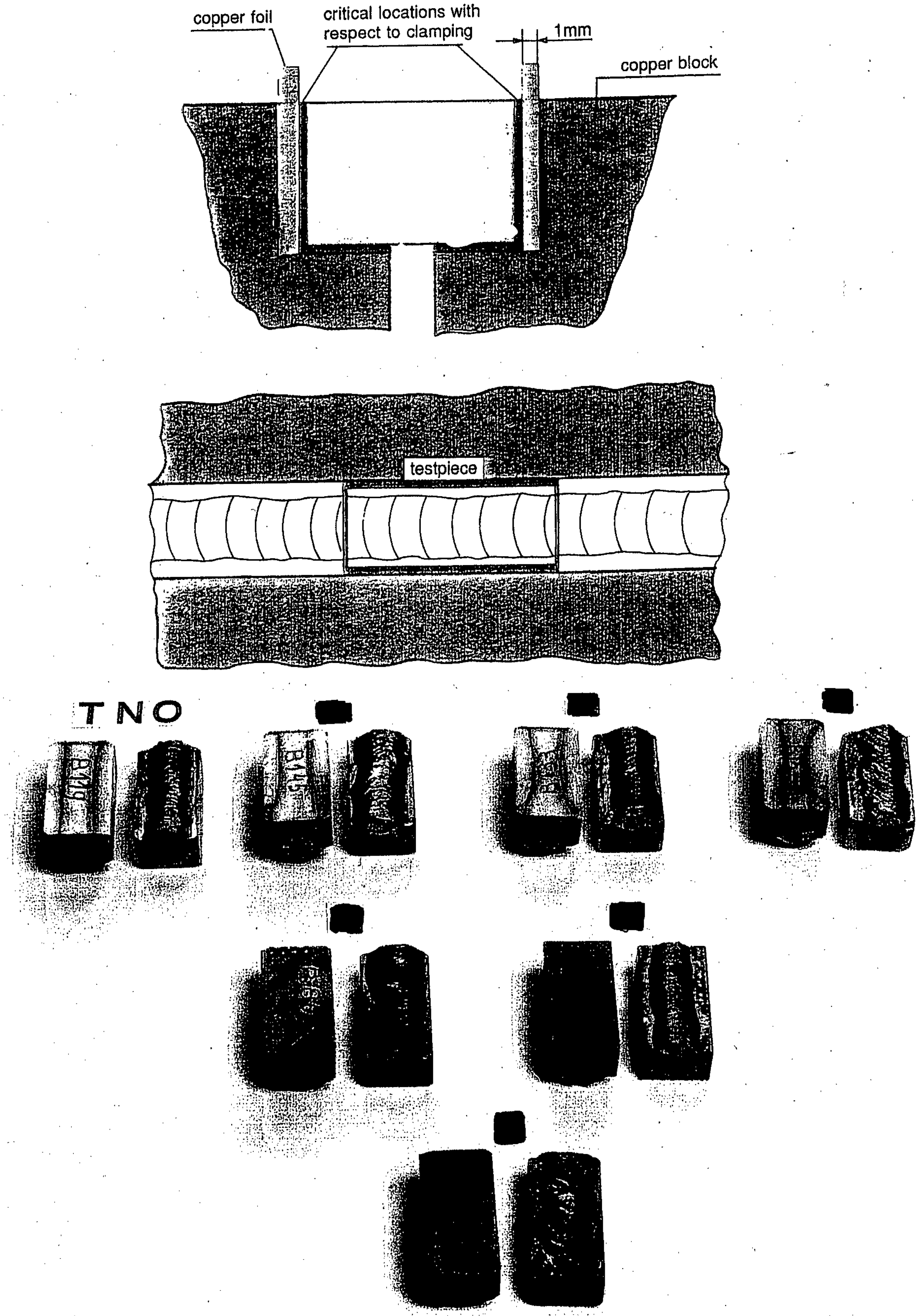
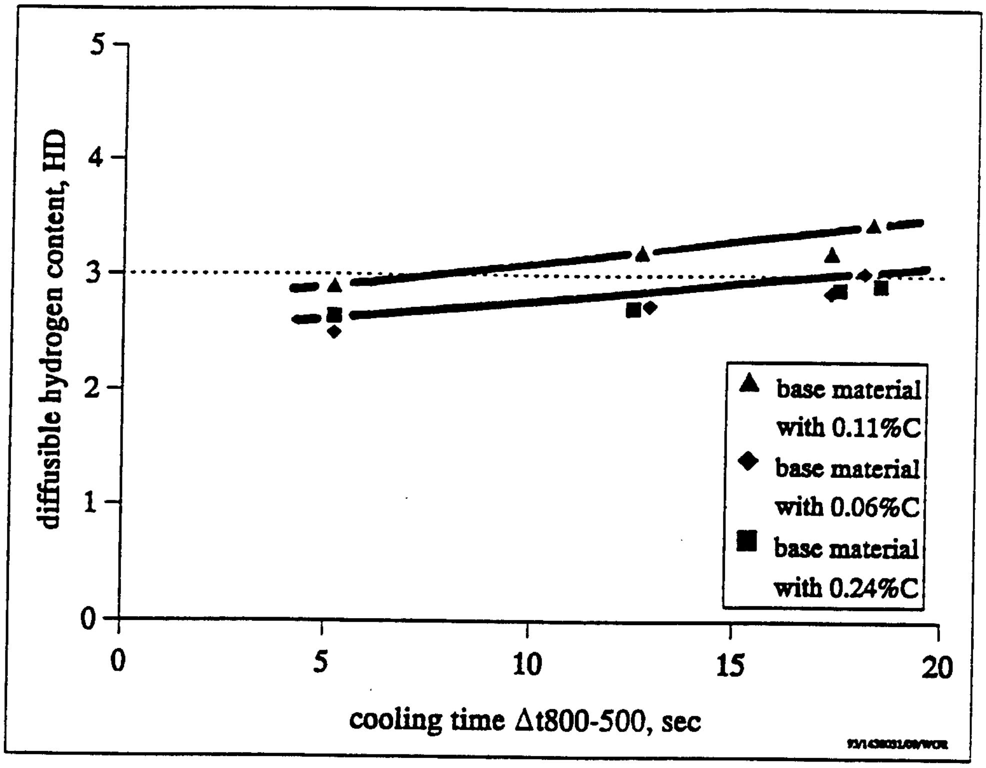


Figure 5 Influence of the clamping conditions of the test pieces during welding. In the optimal condition the clamped regions are not coloured, in the other conditions those regions are more or less coloured.



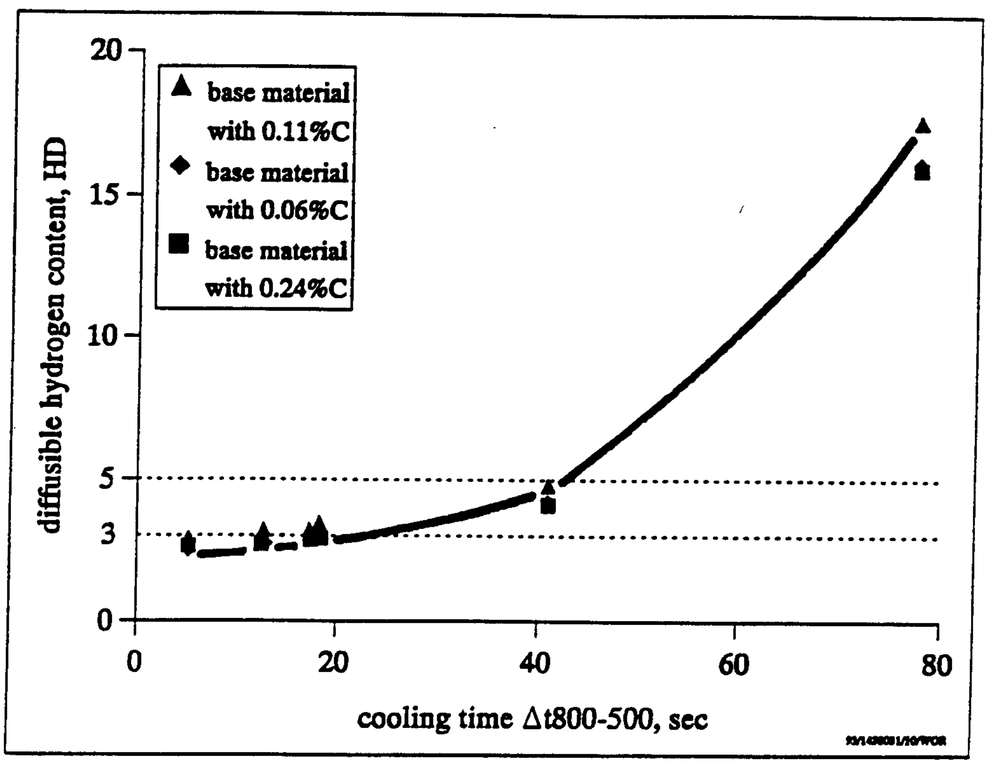


Figure 6 Hydrogen content as a function of the clamping conditions/cooling time Δt 800-500 for three different base materials

Task 3: Development of High Strength Steel Filler Metals

Activity 10: Understanding the Influence of Alloy Additions on Microstructure and Mechanical Properties of Weld Metal from Gas-shielded Processes

Organization: Australia-CISRO-DMT
USA-CSM
UK-DERA

Description: This project is a strategic study in which the influence of well controlled additions of alloying and microalloying elements to experimental gas-shielded cored welding wires will be investigated. Major aspects of the project include manufacture of cored consumables from high purity materials and assessment of details of the welds from these consumables with regard to mechanical properties, microstructure development and influence of non-metallic inclusions.

DERA is using a method for the determination of hydrogen in MMA weld metal is to deposit a single weld bead onto a mild steel test block which is then rapidly quenched and analyzed to determine the diffusible hydrogen content. Work has been conducted to establish whether the measured hydrogen concentration would be affected by replacing the mild steel test block with alternative 550MPa and 690 MPa strength level steels. It was concluded that the diffusible hydrogen concentration was not affected by any of the steel types used as the centre block in test assembly.

Results: A literature review on the subject have been done and published. The effect of Mn, Si, Ti and Al have been investigated and mid-term report and a paper have been published. For Boron series, consumables have been manufactured and characterization of chemical composition, mechanical properties and optical microscopy done. Influence of non-metallic inclusions on microstructure development is under way.

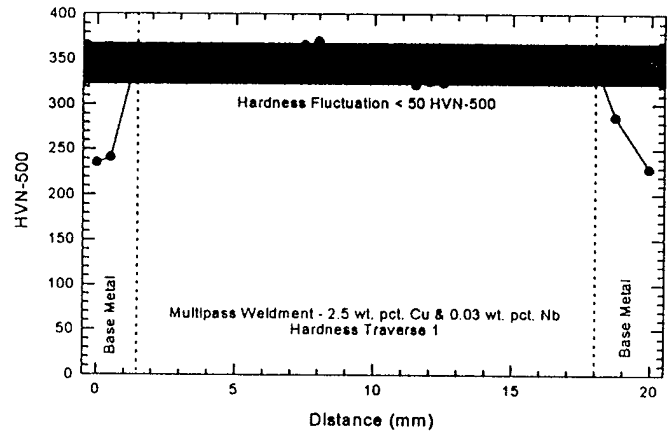
Plans: A visit to CSM for interpretation of the results and to exchange research data, was undertaken in May-June 98 for one month. Subsequent to that one more series to study combined influence of Ti-B is underway.

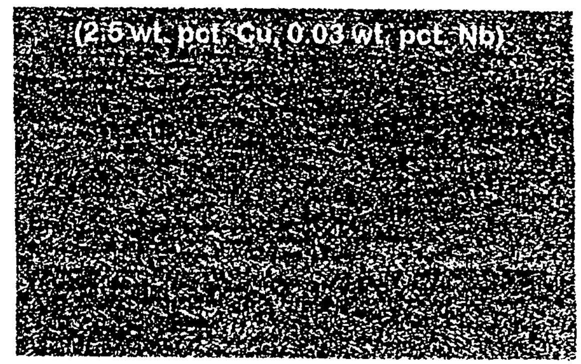
Status: Completed

Completion: 1998, Q4

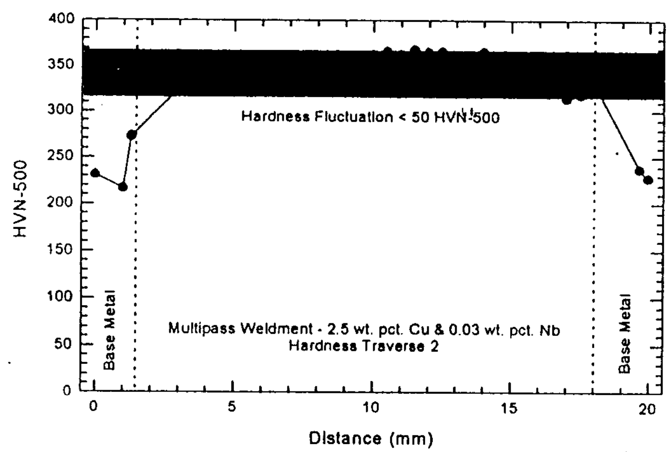
High Strength Steel Welding Research

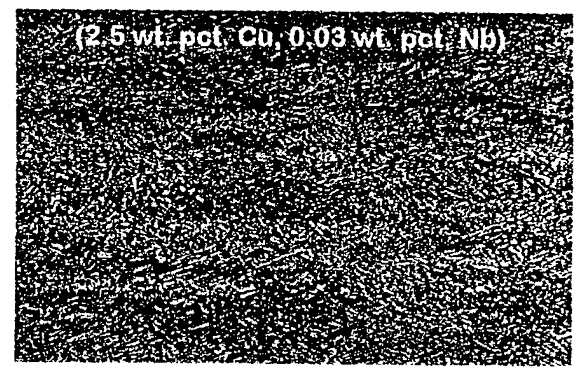
Dual Precipitation Concept - Cu-Nb Additions





As-Welded Microstructure
Bainite/Martensite/Ferrite Mixture

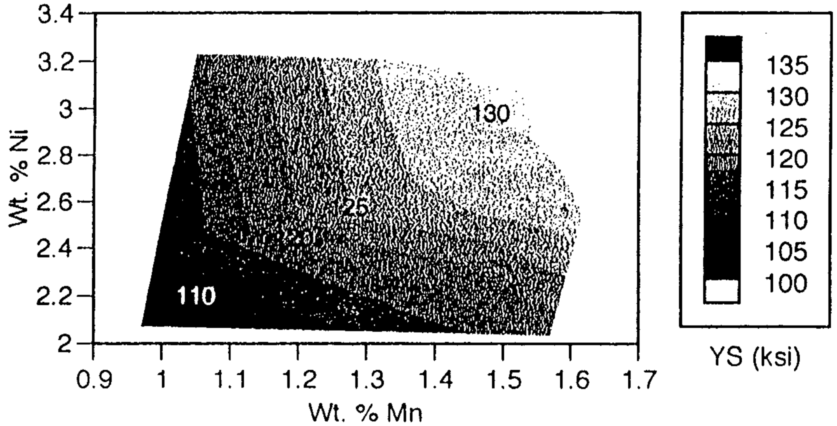




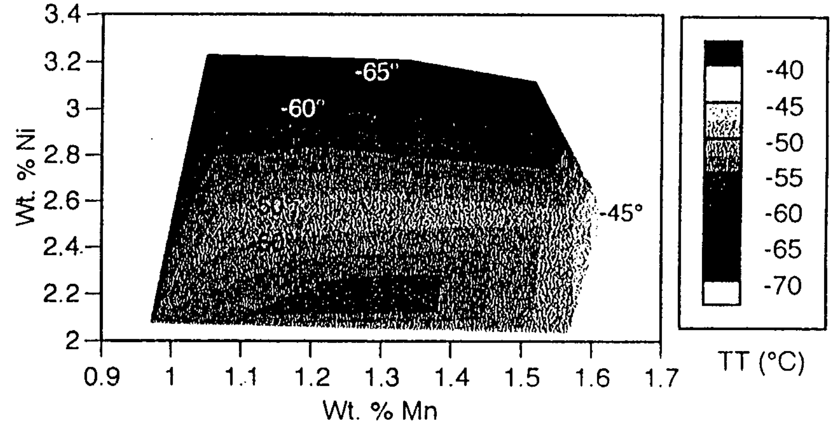
Reheated Weld Metal Microstructure
Predominately FS Phase

More Uniform Across-Bead Mechanical Properties

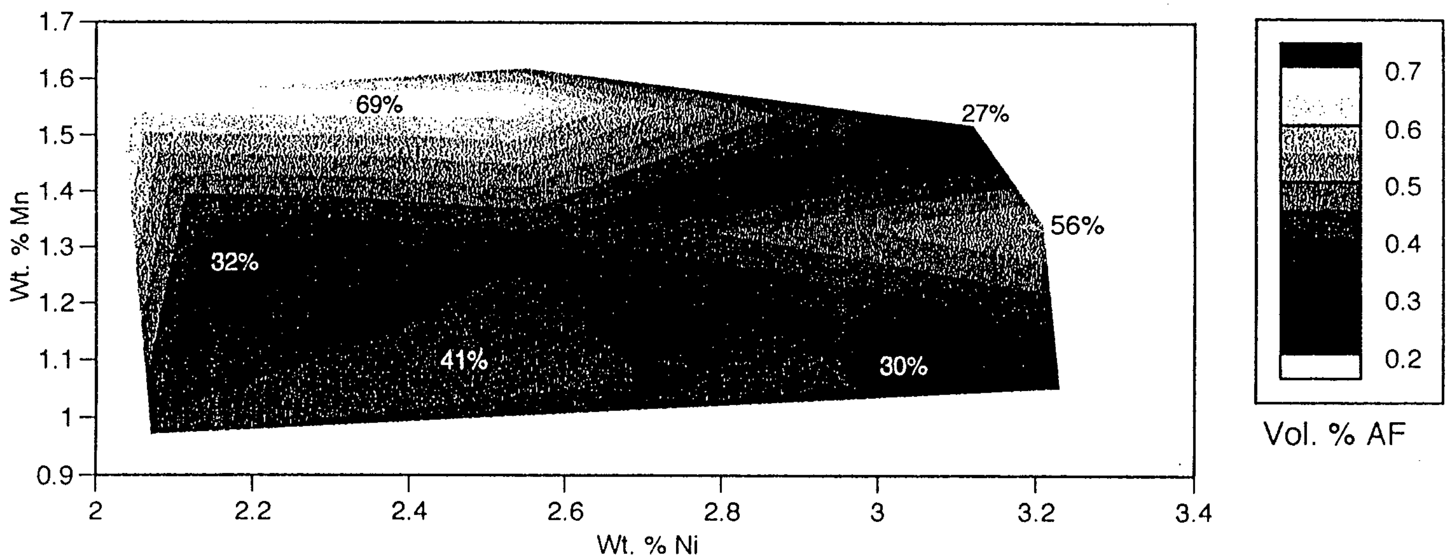
CVN Impact Toughness of Weld Metal with Dual Precipitation is 30% Higher than Welds with Cu or Nb Additions Alone.



Yield Strength (ksi) as a Function of Nickel and Manganese Content for Low Heat Input (1kJ/mm) HSLA Welds



70 Joule Transition Temperature (°C) as a Function of Nickel and Manganese Content for Low Heat Input (1kJ/mm) HSLA Welds



Volume Percent Acicular Ferrite as a Function of Nickel and Manganese Content for Low Heat Input (1kJ/mm) HSLA Welds

CSM-CWJCR

Task 3: Development of High Strength Steel Filler Metals

Activity 11: Evaluation of the Influence of Retained Austenite of Hydrogen Assisted Cracking

Organization: USA-CSM
UK-Cockrane
Australia-DSTO
Canada-DREA
USA-NSWCCD

Description: Retained austenite has been observed to be a significant factor in hydrogen management. In high strength steel weld, retained austenite is a significant high temperature bulk hydrogen trap. The retained austenite may transform to martensite with changes in service temperature and plastic strain, which can cause hydrogen release and resulting in hydrogen cracking. The existence of retained austenite means low reported diffusible hydrogen values when using existing testing methodologies.

Results: Preliminary research has been performed. Results were reported at Pine Mountain, Georgia at the Trends in Welding Research Conference '98.

Plans: NA

Status: in progress

Completion: 1999, Q4

The Role of Retained Austenite in the Hydrogen Management

- OBJECTIVE :
  - Evaluate the Retained Austenite as a Trap Sites
  - Understand the Potential Role of the Retained austenite in Hydrogen Cracking in High Strength Steel Welding
- EXPERIMENTAL WORK :
  - Part A : Hydrogen Trapping in Retained Austenite
    - Thermal Desorption Analysis (Figure 1) for four different contents of austenite Phase (AISI type 304 stainless steel, Super duplex stainless steel, Dual Phase Steel, and Air cooled and Liquid Nitrogen Quenched HSLA steel Weld Metal)
    - XRD to Quantify Retained Austenite
  - Part B : Influence of Retained Austenite Stability on Hydrogen Behavior
    - Retained Austenite Stability by Using XRD
    - Changed Hydrogen Transport Behavior with different Service Condition
- RESULTS :
  - Figure 2 : XRD Result for 4 pct. retained Austenite

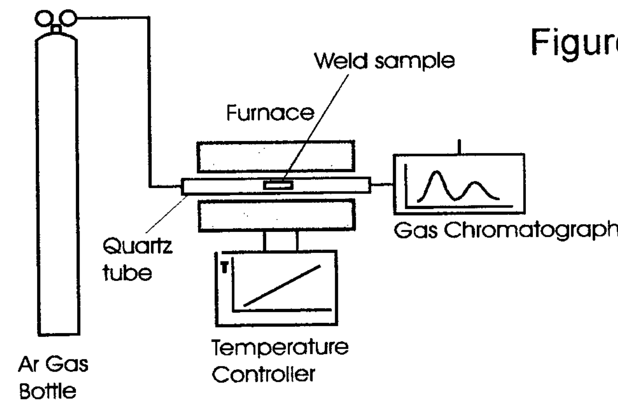


Figure 1

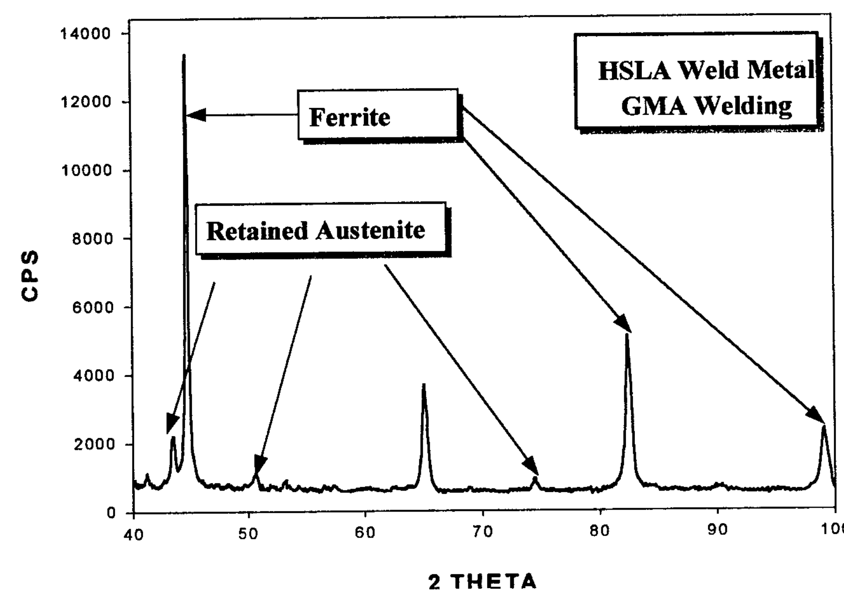


Figure 2

- RESULT :
  - Figure 3: Retained Austenite in High Strength Steel Weld is a Significant High Temperature Bulk Hydrogen Trap
  - Austenite Trapping is associate with a Slow Hydrogen Transport in the Austenite Lattice and is not a Defect Hydrogen Interaction. Understand
  - Figure 4 : Retained Austenite Content was Changed with Different Service Conditions. (Plastic Strain and Reduced Temperature)
  - Figure 5 :XRD Results for Stress Induced Condition
  - Figure 6 : Stress Induced Dual Phase steel shows changed hydrogen transport behavior and Quenching in the Liquid Nitrogen also changed Hydrogen Transport Behavior.

Figure 3

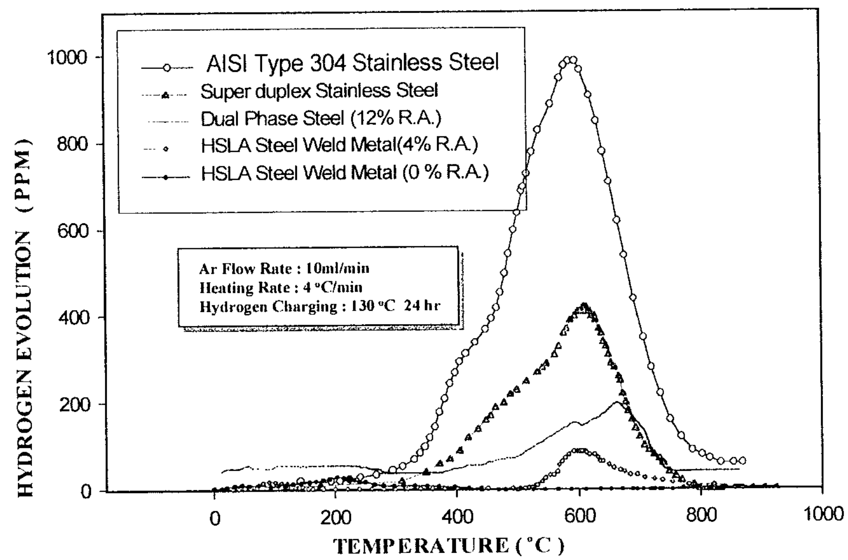
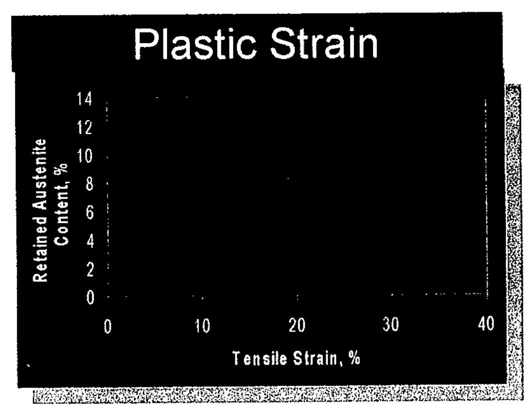


Figure 4



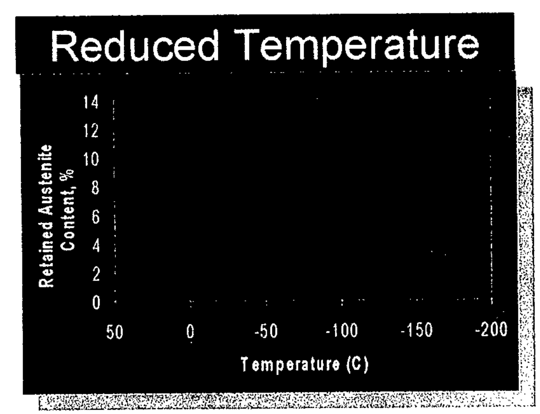


Figure 5

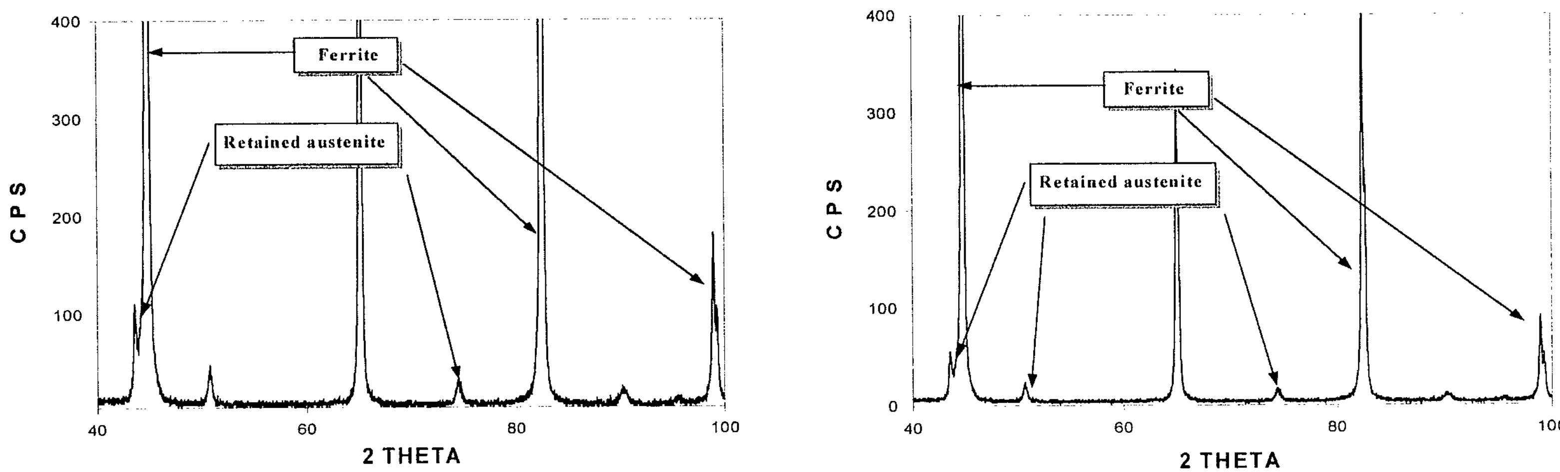
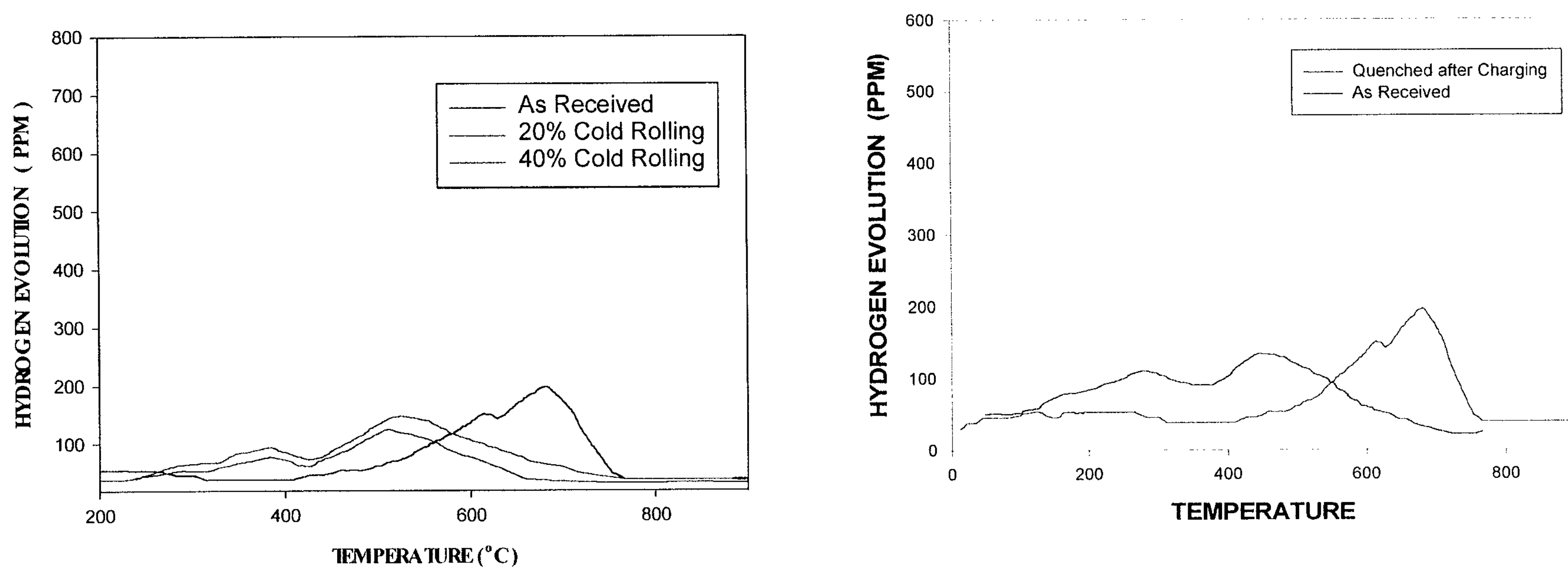
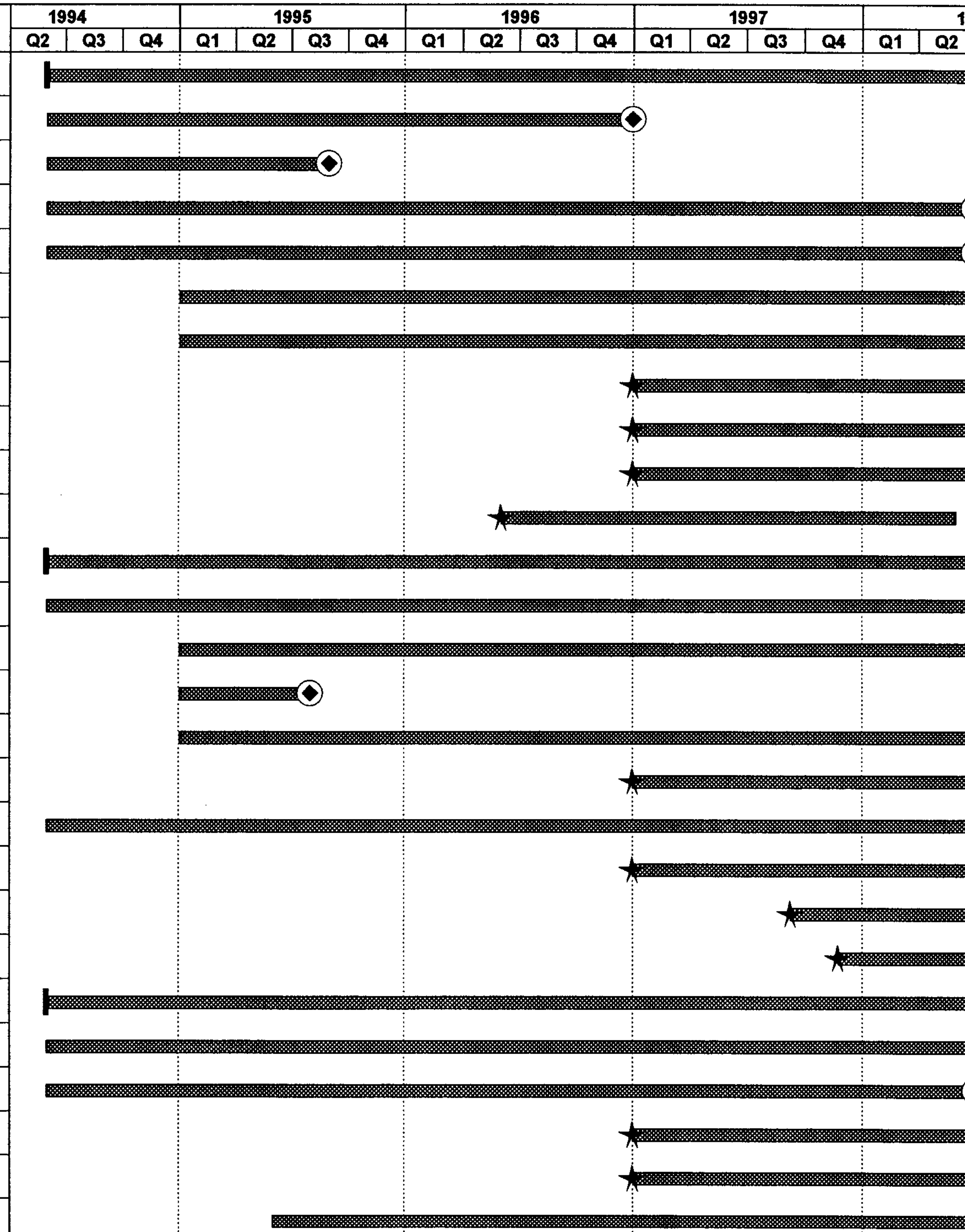


Figure 6

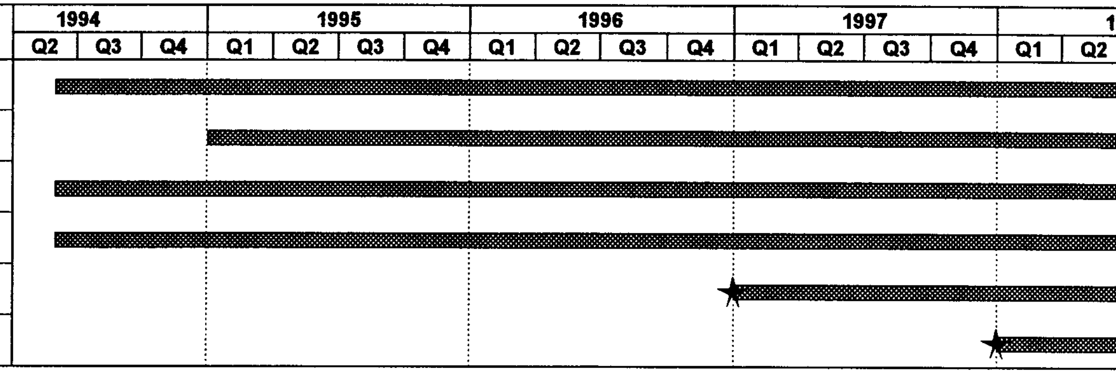


5.0 Gantt Chart (Time Table) for all TASKS and Activities

ID	Task ID#	Task Description	C/P
1	**Task 1**	**R&D of New Weld H-Cracking Tests**	
2	Task 1 Act. 1	Longitudinal Restraint Cracking Test	C
3	Task 1 Act. 2	Modified Gapped Bead on Plate Test	C
4	Task 1 Act. 3	Modified WIC Test	C
5	Task 1 Act. 4	Measurement of KIEAC	C
6	Task 1 Act. 5	J-integral fracture toughness procedures	C
7	Task 1 Act. 6	Fatigue life in H-environments	P
8	Task 1 Act. 7	Worst case scenario for H-cracking in fabrication	C
9	Task 1 Act. 8	Develop Testing criterion for weld repair	P
10	Task 1 Act. 9	Modelling of electronic bonding of hydrogen	P
11	Task 1 Act. 10	Modified Cruciform Test	C
12	**Task 2**	**Weld param. on multi-pass transverse cracking**	
13	Task 2 Act. 1	Hydrogen induced subcritical cracking	P
14	Task 2 Act. 2	Hydrogen cracking and heat input	P
15	Task 2 Act. 3	Risk evaluation of hydrogen cracking	C
16	Task 2 Act. 4	Hydrogen arc sensing and modelling	C
17	Task 2 Act. 5	H-cracking behaviour in a repair weld	P
18	Task 2 Act. 6	electrotransport practice	C
19	Task 2 Act. 7	Charact. of undermatched weldments	P
20	Task 2 Act. 8	Crack Mapping in T-Butt Joint	P
21	Task 2 Act. 9	Hydrogen Content in Multipass Welds	P
22	**Task 3**	**HS-steel filler metals to be used without preheat**	
23	Task 3 Act. 1	Preheat free MMA & FCA Welding Consumables	P
24	Task 3 Act. 2	Development of ULCB wires	C
25	Task 3 Act. 3	ULCB wire evaluation	P
26	Task 3 Act. 4	Evaluation of ULCB MCAW consumables	P
27	Task 3 Act. 5	Fluorite additions to control weld H-content	P



ID	Task ID#	Task Description	C/P
28	Task 3 Act. 6	Aust. decomposition T as H-cracking indicator	C
29	Task 3 Act. 7	Multi-pass weld metal prop. cooperative project	P
30	Task 3 Act. 8	Reduct. of Diff.-H thru the use weld metal H-traps	P
31	Task 3 Act. 9	Anal. method to evaluate weld H-distribution	P
32	Task 3 Act. 10	Alloy add. on micro. & mech. prop. on weld metal	C
33	Task 3 Act. 11	Influ. of retained austenite on HAC	P



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3	Task 1 Act. 2	Modified Gapped Bead on Plate Test	C
4	Task 1 Act. 3	Modified WIC Test	C
5	Task 1 Act. 4	Measurement of KIEAC	C
6	Task 1 Act. 5	J-integral fracture toughness procedures	C
7	Task 1 Act. 6	Fatigue life in H-environments	P
8	Task 1 Act. 7	Worst case scenario for H-cracking in fabrication	C
9	Task 1 Act. 8	Develop Testing criterion for weld repair	P
10	Task 1 Act. 9	Modelling of electronic bonding of hydrogen	P
11	Task 1 Act. 10	Modified Cruciform Test	C
12	**Task 2**	**Weld param. on multi-pass transverse cracking**	
13	Task 2 Act. 1	Hydrogen induced subcritical cracking	P
14	Task 2 Act. 2	Hydrogen cracking and heat input	P
15	Task 2 Act. 3	Risk evaluation of hydrogen cracking	C
16	Task 2 Act. 4	Hydrogen arc sensing and modelling	C
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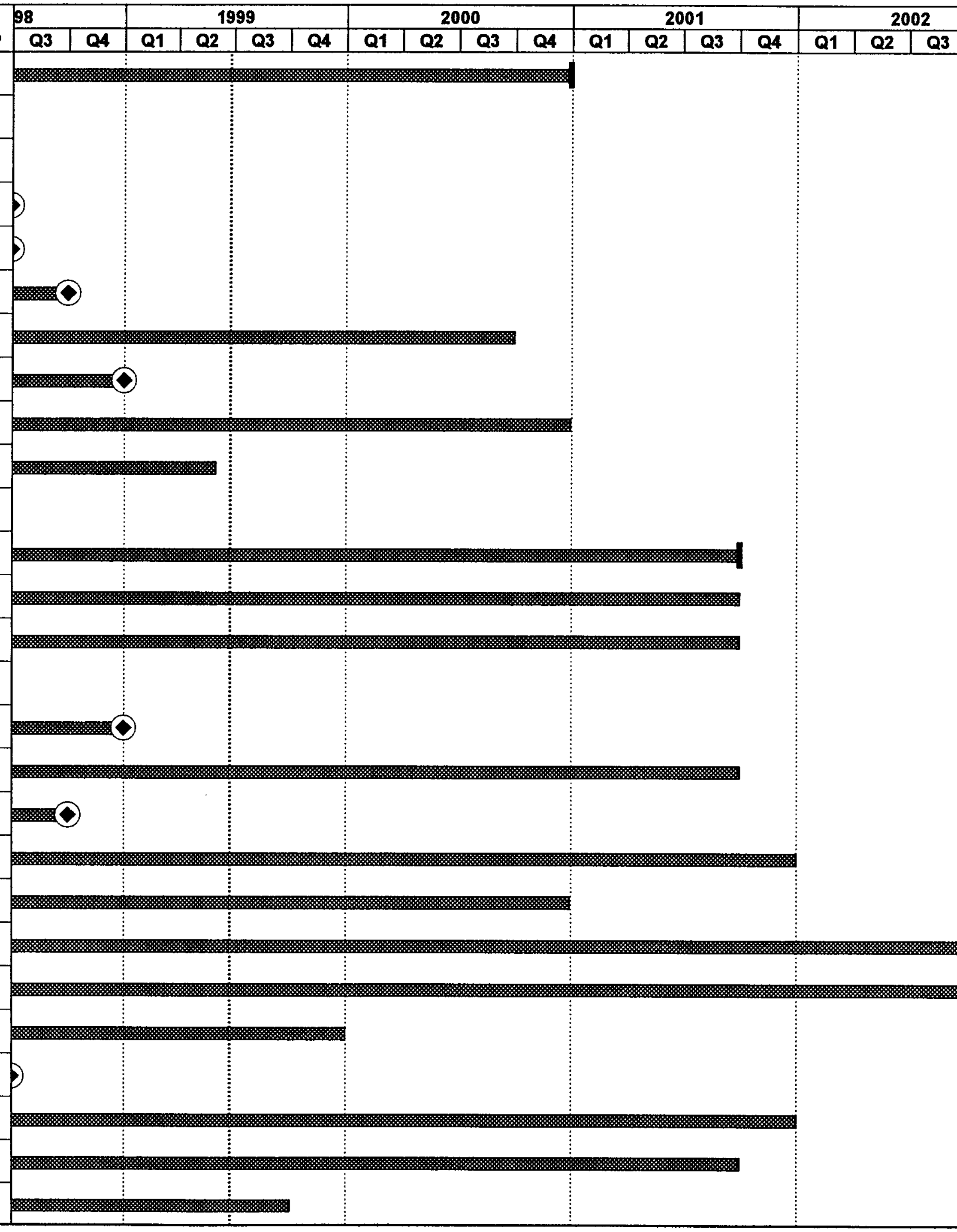

ID	Task ID#	Task Description	C/P	98		1999				2000				2001				2002		
				Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
28	Task 3 Act. 6	Aust. decomposition T as H-cracking indicator	C																	
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33	Task 3 Act. 11	Influ. of retained austenite on HAC	P																	

ID	Task ID#	Task Description	C/P		2003				2004				2005				2006			
				Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
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27	Task 3 Act. 5	Fluorite additions to control weld H-content	P																	

6.0 1996 HYDROGEN MANAGEMENT IN STEEL WELDMENTS JOINT WORKSHOP AND SEMINAR

Melbourne, Australia
23rd October 1996
Sponsored by the US Army Research Office, Australian Defense Science and Technology Organization and Welding Technology Institute of Australia

As part of this collaborative program, a public seminar was held at the Carton Crest Hotel in Melbourne on October 23, 1997. The seminar brought together experts in the field of hydrogen cracking from industry, academia, research institutions and defense agencies, to establish the state-of-the-science, to review the progress of the collaborative research project and to address the feasibility of alternative approaches for hydrogen and preheat management. Seminar papers covered a range of topics form safe hydrogen management practice for today, to the science based development of low-hydrogen consumables for the future. Accordingly, this collection of papers provides a unique opportunity for the reader to become aware of the current directions of hydrogen management in high strength steel weldments. The collection of paper has been published by WTIA.

The on going projects were systemically reviewed with suggestion and inputs from the participants. The five original tasks were reorganized into the three present tasks to promote better use of collaboration in research, development and assessment of quality assurance.

7.0 1998 International Workshop on Hydrogen Management for Welding Applications

This workshop was held on October 6-8, 1998, Camsell Hall Natural Resources, Canada (NRC), Ottawa, Ontario, Canada.

The executive summary and research recommendations are given below in section 7.1 and 7.2.

7.1 EXECUTIVE SUMMARY

The Materials Technology Laboratory, CANMET, in cooperation with the Canadian Department of National Defense, Defense Research Establishment Atlantic; The US Army Research Office, US Army Armament RD&E Center, and the Colorado School of Mines, organized an international workshop on hydrogen management for welding applications. The focus of the workshop was on Hydrogen Management for Steel Welding Applications", particularly for high strength steels and was performed on October 6-8, 1998 at Camsell Hall, National Resources Canada, Ottawa, Canada. This workshop identified major road blocks to the further development of the welding processes, practices and materials in the welding of higher strength steels without hydrogen assisted cracking.

This workshop included both informational keynote presentations and work sessions responding to prepared white position papers. The work sessions will generate recommendations for necessary research, development, education, standardization and policy making. The workshop provided guidance to, and promoted collaboration among the various research and development activities. The workshop also presents assessment of the progress and accomplishments of the presently active TTCP program on Hydrogen Management, assignment S-11.

The white paper sessions are listed as follows:

1. Predictive Methods for Managing Hydrogen in Welding Applications
2. Mechanical Tests for the Susceptibility to Hydrogen-induced Cracking
3. Welding Consumables for Hydrogen Management
4. Hydrogen Management Requirements in Codes, Standards, Specifications and Regulations
5. Mechanistic Understanding of Hydrogen in Steel Welds
6. Hydrogen Measurement techniques
7. Modeling of Hydrogen Behavior
8. The Role of Welding Parameters in Hydrogen Management.

The recommendations of three of working sessions on Mechanistic Understanding (#5), on Modeling (#7) and on Predictive Methods (#1) need to be considered are related and should be part of a combined effort to promote strong coupling between theoretical concepts and the advancements in numerical analysis, modeling and prediction. There was conscience that the state of science offers many new approaches for the selection of welding processes, materials and practices. The ability to predict hydrogen assisted cracking susceptibility for given materials and process parameters can be achieved if collaborative research is vertically focused from specific user requirements down to our fundamental understanding and, our ability to model. The opportunities for successful contributions to hydrogen management resulting higher weld integrity, increased productive and more rapid introduction of the higher strength steels in structural applications.

The recommendations of the three working groups on welding consumables (#3), hydrogen measurement techniques (6), and on welding parameters (#8) offer the fastest turn around in making further advancements in hydrogen management in the welding higher strength steels. These activities need research and development support to take recent accomplishments to the users. In the longer range these activities must be coupled to the more fundamentally driven

activities if the new theoretical, modeling and predictive skills are to make contributions.

The recommendations of two of the working sessions, on Mechanical Testing (#2) and on codes, standards, specifications and regulations (#4), involved in weld integrity need special attention for the other advances to be used in fabrication will require testing, meaningful interpretation of mechanical testing results and new or modified specifications. In the United States there is special interest in this activity area since there are plans to switch military standards and specifications to commercial specifications which require much work to establish of confidence in this transition. Testing for hydrogen cracking susceptibility requires sufficient delay time prior to testing. The amount of this time is considered an important issue since it affects both integrity and productivity. New approaches to this issue need to be explored.

The specific recommendations made by each working session are given below:
Prioritization of the recommendations was not made due the broad spectrum of disciplines and expertise involved in the work shop and insufficient number of participants to make a statistical meaningful prioritization. The specific recommendations made by each working are given below for consideration of research support

HYDROGEN MANAGEMENT FOR WELDING APPLICATIONS

7.2 RECOMMENDATIONS FOR WELDING RESEARCH

1. White Papers on Mechanistic Understanding and Modeling

1. First principles techniques are now capable of discerning the subtle changes in energy associated with the sharp segregation of hydrogen and other impurities to grain boundaries and other planar faults. This capability has come with improvements to computational methods used to solve the Schroedinger equation. Given the improvements seen in the last fifteen years to these approaches, there is every reason to believe that we should continue to see improvement to the point where line defects can be treated with the same accuracy as planar defects are now. Research seeking to improve or accelerate these approaches should be promoted.

2. Analyzing the results of first principle calculations in terms of changes in the charge density remains qualitative. Research establishing quantifiable relationships between features of the charge density and materials properties is necessary to capitalize on the improvements to quantum mechanical calculations.

3. First principles calculations offer the greatest potential as tools to discern the mechanism(s) of hydrogen embrittlement, i.e. whether the process occurs via a decohesion mechanism or via enhanced plasticity. Calculations employing first principle approaches should be directed toward this end.

4. Atomistic calculations using the embedded atom method offer great potential as tools in the study of hydrogen's effect on the properties of materials at the mesoscale. A new approach to the determination of atomic potentials is necessary to model real, as opposed to realistic, materials. These potentials should incorporate the redistribution of charge density associated with embedding.

5. Modeling at the micro structural scale involves the use of statistical and thermodynamic models. These approaches are in principle completely accurate but require knowledge of certain thermodynamic parameters. With the increased accuracy of quantum mechanical techniques, these parameters are now accessible through these first principle approaches. Among the parameters which are accessible to first principle calculations are:

   i. The effects of hydrogen to interfacial and surface energy;
   ii. The effects of hydrogen to interfacial strength;
   iii. The barrier to hydrogen diffusion;
   iv. The effects of hydrogen on elastic moduli;
   v. The effects of hydrogen on dislocation emission from crack tips;
   vi. The binding energy of hydrogen to trap surfaces.

Models combining statistical thermodynamics with electronic models should provide more sophisticated insights into the effects of hydrogen at the microstructural scale.

2. White Paper on Predictive Methods

1. There is a need to develop HAC predictor/indicators for weld metal. It is emphasized that the rich experience base already developed for the HAZ cannot, in general, be adapted to WM because the situation is considered to be quite different.

2. There is a need to develop an understanding of the problems of multipass welding with respect to HAZ HAC. This should include considerations of retained austenite and the occurrence of microphase MA regions where HAC initiation has been observed.

3. The significance of HAZ or WM hardness as an HAC indicator is controversial, e.g., notable and important exceptions to the general trend that the risk of HAC increases with hardness have been found in recent years. Nonetheless, the significance of hardness as an HAC indicator should be thoroughly investigated and evaluated because it is so widely used in the industry.

4. Residual stresses should be incorporated in all weld HAC indicator studies. Moreover, the approach should focus on local stresses (e.g., potential HAC sites) and should include geometry and processing effects.

5. There is a need to develop an understanding of WM/HAZ coupled effects, e.g., the effect of relative transformation temperatures.

6. Service failures initiating from hydrogen penetrating either the WM or HAZ are considered important and should be the focus of further workshop review and study.

7. Predictor indicator schemes must be based on user friendly procedural variables, e.g., preheat temperatures, interpass times, chemical compositions, heat input variables, etc.

8. Whenever possible, predictive/indicator schemes should be computer based. In particular the neural network methodology is seen to have considerable potential with regard to the HAC problem.

3. White Paper on Hydrogen Measurement

The following topics will be important in future research for hydrogen measurement methods:

Development of correlations for diffusible hydrogen content from out-of-position welds and multiple-pass welds.

1. Development of advanced electronic techniques for determination of moisture content in electrode coverings and flux cored wires;

2. Development of advanced electromagnetic techniques for determination of diffusible

hydrogen content;

3. Development of advanced electromagnetic techniques for determination of hydrogen distribution across the weld.

4. White Paper on Mechanical Tests

Tests for the susceptibility to hydrogen-assisted cracking will serve one or more of three functions:

(i) Enable one to determine safe welding parameters which would guarantee freedom from hydrogen-assisted cracking in production or during a repair

(ii) Allow the ranking of consumables or processes in terms of resistance to hydrogen-assisted cracking or

(iii) Provide a research tool that allows for the independent control of the major variables which lead to hydrogen-assisted cracking (i.e. microstructure, stress and hydrogen concentration).

When choosing a test for hydrogen-assisted cracking resistance it is important to:

(i) recognize that each test will have a bias toward cracking in the HAZ or the weld metal and that it may not adequately measure the cracking resistance in the other location

(ii) know *which function* of a hydrogen-assisted cracking test is actually needed

(iii) ensure that the candidate test(s) fulfill the requirements of that function.

From the analyses in the preceding sections it is apparent that there are existing tests which adequately satisfy the functional requirements of both the ranking and the fundamental test functions. However, there are few tests (if any) which could be used to determine welding parameters which would guarantee freedom from transverse hydrogen-assisted cracking in weld metal during production or in a repair scenario. This is clearly an area for future effort.

5. White Paper on Welding Consumables

Continual advancements in consumable developments over the last 30 years have expanded their usage into more critical applications requiring hydrogen management. Although a wide variety of products are available, additional developments over the next decade are needed to consistently achieve the lower diffusible hydrogen levels required for today's new steels. Following are the major recommendations that should accomplish this goal, if they are implemented and successfully completed.

- Continue research on using fluorides for reducing diffusible hydrogen.
- Improve consumable manufacturing methods to reduce hydrogen sources.
- Continue investigations on the effectiveness of hydrogen getters or traps on reducing

diffusible hydrogen.

- Explore new alloy systems that are more resistant to hydrogen assisted cracking problems.
- Improve consistency of low hydrogen consumables and the methods used to measure diffusible hydrogen.

6. White Paper on Welding Parameters

1. Analytical techniques are needed to investigate the impact of welding parameters on the level and distribution of diffusible hydrogen in the weld. The effect of individual factors, including amperage, voltage, travel speed, current densities, transfer mode, electrode extension as well as the interrelationship of these parameters must be studied. The effects of welding parameters on diffusible hydrogen must be correlated with the microstructural development resulting from the selection of these parameters. The interrelationships between welding parameters, microstructural development and hydrogen effusion (cooling rate from 3000 to 100^0C) should be investigated. The outcome of these investigations should be to develop analytical practice to select a resilient set of welding parameters for the various steels and welding processes suitable for automated control.

2. Analytical techniques are needed to investigate the role of edge preparation, joint configuration, and welding position on hydrogen pick up and stress distribution in the weld joint.

3. The role of weld through primers and anti-spatter compounds as hydrogen sources should be investigated.

4. Ongoing research on the impact of shielding gas composition on the diffusible hydrogen content of deposited weld metal should continue. Gas nozzle design should be modelled to aid in developing improved designs which reduce the introduction of contaminate gases.

5. Since residual stress distribution relative to the weld achieves a region adjacent to the weld with strain gradient conditions favorable to hydrogen transport, the resulting hydrogen distribution produces a high hydrogen content adjacent to the fusion line in the heat affected zone, a location with the most likely hydrogen cracking susceptibility. New analytical techniques need to be developed to calculate the resulting weld hydrogen distribution for a given set of welding parameters.

6. Research is needed to investigate how welding parameters affect the transient time in the 3000 to 100^0C range and thus their impact on hydrogen diffusion from the weld. Research continues to be needed in developing new or improving existing relationships for selecting the proper preheat temperature to maintain diffusible hydrogen contents below critical levels.

7. Modelling of multiple pass welding is needed to aid in understanding the potential benefits of temper bead sequencing and the redistribution of diffusible hydrogen.

7. White Paner on Codes and Standards

1. The information in this paper emphasized standards and specifications in the United States and Canada. A white paper review, similar to this paper, summarizing hydrogen management requirements in codes, standards, specifications, and regulations in other industrialized nations such as the UK, Japan, and other European countries would be useful.

2. The United States is planning to switch from military standards and specifications to commercial specifications wherever possible. Several differences in the requirements between military specifications and commercial electrode specifications and fabrication documents were presented in this paper. A strategy or plan to address these differences is needed. Similarly, the United States and possibly other countries would like to adopt certain ISO standards in order to increase the ability to conduct international business. The differences between certain country-specific standards and similar current and planned ISO standards need to be identified and addressed.

3. The delay time prior to the final inspection of a welded structure was considered to be an important issue. Delay times that are too short may result in undetected hydrogen cracks. Delay times that are too long hurt productivity and increase the cost of the fabricated structure. The current recommended delay time prior to inspection for hydrogen cracks was found to vary significantly between the different fabrication documents reviewed. The current proposed delay times may not reflect the improvements in the weldability of the plate materials and low hydrogen welding consumables that are available today. Developing a rational criterion for determining the minimum delay time for weld inspection, based on the materials used, the thicknesses involved, and the criticality of the application is desirable.

8.0 NEW(MAT-TPI-0-22) OPERATING ASSIGNMENT

The following Activities will carry over from MAT-TP1-0-13 operating assignment to the new operating assignment, MAT-TP1-0-22 as one of the new tasks.

Task	Activity	Description	Organization
1	6	Fatigue Life in Hydrogen Environments	USA-Army Benet Lab-ARDEC
1	8	Develop Testing Criterion for Weld Repair	Australia-DSTO, ASC,USA-NSWCCD
1	9	Modeling of Electronic Bonding of Hydrogen in the Zone Ahead of Sub-critical Cracks in Ferrous Alloys	USA-Army ARL,USA-CSM, Australia-DSTO
2	1	Hydrogen Induced Sub-critical Cracking	Australia-DSTO
2	2	Hydrogen Cracking and Heat Input	Australia-DSTO
2	5	Modeling of Hydrogen Cracking Behavior in a Repair Weld	Canada-DREA
2	8	Cracking Mapping in a T-Butt Joint	Australia-DSTO, USA-NSWCCD, Canada-DREA
2	9	Hydrogen Contents in Multipass Welds	UK-DERA, Canada-DREA, USA-NSWCCD, Australia-DSTO
3	1	Preheat Free MMA and FCA Welding Consumables	Australia-DSTO, CSIRO-DMT USA-NSWCCD, Canada-DREA
3	3	ULCB Wire Evaluation	Australia-DSTO,USA-NSWCCD
3	4	Evaluation of ULCB MCAW Consumables	USA-NSWCCD
3	5	Fluoride Additions to Control Weld Hydrogen Content	USA-CSM
3	7	Multiple Pass Weld Metal Properties Cooperative Project	USA-CSM, Australia-CSIRO
3	8	Reduction of Diffusible Hydrogen Through the Use of Weld Metal Traps	USA-CSM, Lincoln Electric
3	9	Analytical Methods to Evaluate Weld Hydrogen Content and Hydrogen Distribution	USA-CSM, Lincoln Electric, SUNY Albany
3	11	Evaluation of the Influence of Retained Austenite on Hydrogen Assisted Cracking	UK-Cockrane, Canada-DREA, USA-NSWCCD, CSM, Australia-DSTO

8.1 OPERATING ASSIGNMENT SUMMARY

Assignment Title: **Reference No:** MAT-TP1-0-22

LIFE CYCLE COST REDUCTION FOR WELDED HIGH STRENGTH STEEL CONSTRUCTION

Focus Officer: Prof. D.L. Olson **Status:** New **Type:**

Start Date: October, 1999 **Estimated Completion Date:** 2003

Estimated Manpower Effort:

Aus	Can	NZ	UK	US
min 1.5	min 2	----	min 1	min 10

Principal CTA: Cost Effective Metallic Materials

Associated CTA: Armour, Ammunition and Ordance

Defence Relevance: For the foreseeable future, welded high strength steels will remain the most extensively used material in ships, submarines and armoured vehicles. Reduction in maintenance budgets, emphasis on building less expensive but longer life systems and use of systems beyond their design lives require improved methods of welding and inspection. Significant savings and improvements in quality are believed to be possible by: better managing hydrogen, through improved detection methods, improved understanding of kinetic issues and improved welding consumables; better dealing with defect acceptance criteria, especially for high toughness materials; and understanding and optimization of welding procedure variables. At least one aspect of the welding problem, hydrogen-cracking avoidance is, closely related to hydrogen problems created by advanced propellants used in heavy guns. There are significant opportunities for cross-disciplinary collaboration, which will benefit both groups. The Defence Department of all TTCP nations are supporting work on steel welding, some at a very high level. As well, the U.S. Army is supporting work on hydrogen embrittlement of guns.

Scientific Objective: To share information and do collaborative research on hydrogen management in welding, defect acceptance criteria and understanding and optimization of welding procedure variables and other welding topics defined by the participants. Specific objectives include: developing recommendations on inspection delay time in development of hydrogen cracking tests useful for procedure development, understanding the effect of welding variables on cracking and properties, and developing more rational defect acceptance criteria.

Outline Program (Start to Finish): A first meeting will be held in Fall '99. By this time program will be finalized and participants in each activity identified. A first (hopefully final) report on inspection delay times will be given by the end of 1999. A mid-course correction will occur in 2001. The final report will be complete by Nov 2003.

Progress (Achievement/Difficulties) During Last Year: New assignment that will follows on from Operating Assignment 0-13 in 1999. At the 0-13 meeting in Oct. '98, plans for a follow on assignment were discussed. So far, collaborators have been identified in Canada, the United States and Australia. A plan for collaborative work has been defined and agreed to by workers in these countries.

Milestones for 1998-1999: In 1998-99, operating assignment 0-13 will be completed and a final report prepared. For the new assignment, a kick-off meeting will be held in Colorado or Benet or England or (?) or in the Fall of '99. Some parts of the program will be well underway at that time.

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